# Assessment of the Transfer Penalty for Transit Trips in Downtown Boston

## A GIS-based Disaggregate Modeling Approach

By

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Submitted to the Department of Urban Studies and Planning

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## ABSTRACT

This research aims to examine the impacts of transfers since transfer activities have significant implications not only for the daily operation of a transit system, but also the integration and coordination between transit lines. Transfers affect transit system performance in at least two respects. On the one hand, the use of transfers in the design of transit services provides more options for the transit operator in terms of area coverage, resource allocation, and flexibility. These factors result in better overall service. On the other hand, transit users do not seek to make transfers on their trips unless there is no alternative or the transfer offers a compelling performance advantage for a given trip. Exploring this trade off associated with transfers helps in understanding passenger dissatisfaction with the transfer, or the transfer penalty.

A trade off between making a transfer and extra walking time is explored using a binary logit choice model to review the existence of the transfer penalty, the components inside the penalty, the effects of the urban environment outside the transit system, and the variation of the penalty across trip and personal characteristics. The MBTA subway system in Downtown Boston is used for the analysis, and GIS techniques are used extensively for data processing and results display.

The study shows that there is indeed a perceived transfer penalty among MBTA subway riders. Transfer walking time, transfer waiting time, the change of level, and the existence of concession capture the majority of the penalty. The remaining part is explained by the general condition of the subway transfer station, and the in-vehicle travel time spent on making a transfer. The study also shows there is a variation of the transfer penalty across different transfer stations. The urban environment in Downtown Boston as explained by measures, such as sidewalk width, land use, open space, and topology, also has a significant impact on the transfer penalty. In particular pedestrian friendly Downtown area encourage riders to leave the subway system early and walk further. The penalty is found to be largely independent on the trip and demographic characteristics though this finding may be affected by the population being limited to those who already choose the subway system to reach their final destinations in Downtown Boston.


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# Chapter 1 Introduction

This thesis will present a method for assessing the transfer penalty that exists in a public transportation system. It is believed that a typical transfer has an associated penalty because of its inconvenience. However, because of the lack of adequate assessment techniques, it is still not clear what elements are embedded in this penalty, and how to reduce this penalty to improve service quality and in particular service integration. The thesis adopts a new method using a disaggregate data set in a GIS environment, which is able to explore the elements of the transfer penalty, and how different factors, such as level of service, demographic characteristics, and pedestrian environment, affect the transfer penalty. The method is believed to be more precise than previous methods, and allows a more comprehensive understanding of the transfer penalty.

In this thesis, the method is applied to Massachusetts Bay Transit Authority (MBTA) subway system in Downtown Boston. The MBTA runs four subway lines and 21 stations in Downtown Boston including the four major transfer stations, which accommodate a huge number of transfers within the system. The analysis of the transfer penalty should be helpful to the MBTA in improving service coordination, and increasing both ridership and customer satisfaction.

## 1.1 Transfer Activity and the Transfer Penalty

Transit networks are systems of inter-connected routes, which must function together as an integrated system. A key component of the integration is easy and convenient transfers for its users. In most transit systems in North America, 10% to 30% of riders make at least one transfer to reach their final destination, and in some systems, this percentage exceeds 50% (APTA, 2000). In Boston, 24% of subway trips involve at least one transfer, while in Chicago, more than 50% of CTA passengers transfer during their typical trip. Thus transfers play a significant role in daily transit operations for these systems in terms of customer satisfaction, ridership, and efficiency (Crockett 2002). Transfer activity also indicates how well different service lines are connected with each other, and how the transit system interact with other transportation systems, such as bus, auto, and pedestrian.

Although transfers are important to transit riders, most riders do not like to transfer. Transfers may require riders to walk long distances or utilize several stairwells in order to board the connecting transit vehicle. Transfers may expose riders to physical discomfort if they are made to wait in unprotected locations, subject to inclement weather or unduly loud ambient noise. Passengers may just miss their transfers vehicles and be forced to wait long periods of time for the next arriving vehicle. The reluctance of transit users can be thought of as a type of transfer 'penalty'.

The transfer penalty measures the disutility of a transfer option compared to an alternative non-transfer option. It has long been recognized as an important consideration in model development, service design, and the performance of a transit system. A major objective is designing a transfer system is to promote ridership, and to reduce rider difficulty through improved transfer performance (Wong 2000). A clearer understanding of the transfer penalty will enhance ridership forecasting, network design, station design, service design, service management, and the marketing strategy of a transit system.

### 1.2 The Mist of the Transfer Penalty

Despite its importance, little is known about the transfer penalty. The transfer penalty has been defined as different things in different studies. For example, the penalty can be defined as a single thing including all the effects of time, cost, and inconvenience factors. It can also be defined as that in addition to the time and cost involved in the transfer. It can also refer to that separate from time, cost, and connectivity factors. The different "faces" of the penalty is a critical issue that will be explored in this thesis. In this research the transfer penalty will be broken into different pieces step by step to see what elements in the penalty can be measured and controlled, and what can not.

The transfer penalty is affected by multiple factors. It may be affected by the design of transfer stations as well as by the layout of a transit network. It may be determined not only by the transit system, but also by factors outside the system such as the urban environment, land use, road network, topology, urban form etc. It may also vary with particular riders who use the transit system based on their trip and demographic characteristics. All these factors should be considered developing a comprehensive understanding of the transfer penalty.

The transfer penalty is not an absolute value. It is a result of the comparison between the utility of a transfer option and alternative non-transfer options. If there are several non-transfer options, this will add complexity to the penalty analysis. For example, if riders can choose either bus, car, or walk to their destinations after they leave a subway system, there will be four more two paths included: bus transfer path, bus non-transfer path, car transfer path, and car non-transfer path. The work load of data processing will be tripled. If other factors affect the utility of the alternative non-transfer option, they will also affect the transfer penalty.

For these reasons, the transfer penalty has not been fully studied. In this research a new method is developed to solve these problems, so that the transfer penalty can be measured and analyzed more accurately and in more detail.

### 1.3 Assessment Method

Transfer activity is a two-edged sword as it affects the performance of a transit system. On the one hand, the use of transfers in the design of transit services provides more options for the transit operator in terms of area coverage, resource allocation, and flexibility, resulting in better overall service (Lin 1998). On the other hand, transit users do not seek to make transfers on their trips unless there is no alternative or the transfer enables them to take advantage of a mode that offers a compelling performance advantage for a given trip (Lin 1998). The benefit of transfers includes the saved travel time, cost, and possible inconvenience of traveling when choosing the alternative mode to get the destination. The basic method to measure the penalty is based on the trade off between the different aspects of a transfer.

There are two situations in the trade off. In the first situation, in order to avoid a transfer, people may choose not to ride the transit system but take an alternative mode. In the second situation, people still choose transit, and the transfer trade off exists during a part of their trip. For example, they can transfer at a transfer station to get closer to their destination so they can walk less, or they do not transfer but access their destination directly by walking a longer distance. In the first case, the trade off is between transit and auto modes, and in the second case, the trade off is largely between extra time spent walking and on transit. Previous studies have focused on the first trade off to estimate the transfer penalty. The advantage of such a method is that the analysis covers all travel modes in a large area, and is thus applicable to defining the role of the transit system within the region as a whole. However, this approach usually does not provide detailed information on the transfer itself and thus results in imprecise findings. Chapter 2 will discuss this in more detail.

Compared to the first trade off, the trade off between walking and transit time has many advantages in terms of transfer penalty analysis. First, this method can be based on data from on-board surveys for specific transit systems, which provides more detailed information on the trips within the system, such as where to access the system, where to transfer, and where to egress from the system. Information on the transfer and non-transfer options can be calculated more accurately. Second, the method allows disaggregate analysis based on individual trips, which makes the analysis easily performed in a GIS environment. Third, the method can incorporate a large amount of trip and demographic information into the analysis that the first method is unable to. The limitation of this method is that it is unable to examine how transfers affect people's choice to use a transit system. Chapter 2 will describe this method in more detail.

In this research, binary choice models will be developed to estimate the transfer penalty. Data from an on board survey is processed in a GIS system, yielding precise information on travel paths. The GIS system also allows the combination of transit system variables with land use and pedestrian environment variables. All data will be entered into the choice model for analysis. Models are developed in two series to capture the effects of station design, network design, environmental factors, and trip and demographic characteristics on the transfer penalty. Chapter 5 will describe the two model development series in detail.

### 1.4 Objectives

In summary, the motivations behind this research include 1) the transfer penalty is critical to the daily operation of a transit system; 2) it is a key indicator to examine how well different service lines and passenger transportation systems are connected; and 3) it helps test the interaction between station design and network planning, between the transit system and the outside environment, and between the system and system users in terms of the transfer penalty. Therefore, the objectives of the study are

1. to explore the extent to which the reality and perception of the transfer penalty affects public transit use;
2. to investigate how transit users make trade-offs between travel time and other aspects of the transfer;
3. to explore the implication of the transfer penalty in transit station design and network planning;
4. to investigate how system (endogenous) factors and environmental (exogenous) factors affect the transfer penalty;
5. to investigate the extent to which the transfer penalty varies as a function of personal and trip characteristics;
6. to give suggestions and research directions on the integration and coordination of passenger transportation systems.

### 1.5 Thesis Structure

This thesis is organized into six chapters. Chapter two describes a framework for the penalty analysis. Based on the framework, the results of previous studies on the transfer penalty, and the methods used are also presented.

Chapter three covers the study area of Downtown Boston, the MBTA subway system, the data set for analysis, and the method that will be used in this thesis. A binary choice model is developed and possible variables are also presented.

Chapter four outlines how data is processed in a GIS system. This is the most time consuming part of this research. The major task is to generate four types of trips, and calculate the time variables associated with alternative travel paths. A statistical summary and the definition of all variables are provided at the end of this chapter.

Chapter five covers the development of a series of models. The first model includes only the simplest variables, and the transfer penalty includes the effects of all the system factors. Next, more variables are added and the residual pure transfer penalty becomes clearer. A comparison will be made to examine how the penalty decreases with the addition of new variables. Then, variables from the outside environment are added to test their effects, and a comparison is made between these variables and the system variables. Lastly, trip characteristics and demographic variables are added to check their impact on the transfer penalty.

Chapter six gives a brief summary of the results of model specification, and suggests directions for future studies.

# Chapter 2 A Method for Assessing the Transfer Penalty

This chapter describes the roots of the transfer penalty, and defines different groups of factors that may affect the penalty. Assessment methods of the penalty in current practice and previous studies are analyzed, and their findings are compared. A new method is described based on the trade off between extra time walking and time on transit. A binary choice model is developed.

## 2.1 Roots of the Transfer Penalty

It is believed that trip generated anxieties, walking and waiting, safety, and pre-trip cognitive load are major components that comprise the transfer penalty. Therefore, the value of the transfer penalty can be accounted for in the amount of physical, cognitive (mental), and affective (emotional) effort that must be expended in the transfer (Wardman 2001). Physical effort when transferring is required for walking, waiting, or carrying. Cognitive effort is needed to collect and process information during a transfer. Route familiarity will reduce the amount of cognitive effort needed. Affective effort includes uncertainty about connections, arrival, or personal vulnerability (Wardman 2001). Factors that can influence one or more of the efforts determine the value of the transfer penalty.

## 2.2 Factors Affects the Transfer Penalty

There are two ways to categorize factors that may affect the transfer penalty. If we focus on how transfer stations and the travel paths affect the transfer penalty, factors can be grouped into station factors and path factors. Station factors include transfer walking time, transfer waiting time, and the characteristics of transfer facilities. They capture the contribution of transfer stations to the transfer penalty, and have clear implications on station design. Path factors include in-vehicle time, walking time, and environmental characteristics along both transfer and non-transfer path. They have implications on network design and planning.

If we focus on how the transit system and outside environment affect the transfer penalty, factors can be categorized into system factors, and environmental factors. System factors include the transfer station factors plus the in-vehicle time in the transit system. Environmental factors include walking time, and environmental characteristics along both transfer and non-transfer paths outside the transit system. In addition to the four groups, there are trip and demographic factors that may affect the transfer penalty. All these factors will be analyzed in this research. Table 2-1 lists the five groups of factors.

**Table 2-1 Factors Affect the Transfer Penalty**

| | **Variable** |
|---|---|
| Station Factors | Transfer walking time, Transfer waiting time<br>Change of level, concession |
| Path Factors | In-vehicle time, Walking time<br>Land use, Open space, Street Network, Topology |
| System Factor | Station Factors + In-vehicle time |
| Environmental Factors | Land use, Open space, Street Network, Topology |
| Trip & Demographic Characteristics | Age, income, gender, household size, occupation, car ownership, license, trip purpose, trip time, frequency, fare type, |

### 2.2.1 Station Factors

The transfer penalty is affected by the characteristics of the transfer facility. Does it require a change of level when transferring from one line to another? How far is it to walk from one platform to another? Is it convenient when waiting for the bus or train to transfer? What are the conditions in the transfer station? In this research, the system factors include two sets of variables: first the transfer walking time and the transfer waiting time variables, and second all other variables, such as the existence of escalators or concessions, the width of the platform, the ventilation of the station etc. We expect that the time variables will definitely affect the value of the transfer penalty, though this still needs to be tested. For example, the results from Hunt (1990) indicate that the act of transferring accounts for most of the transfer penalty, while waiting time does not play a large role. The effects of other factors on the transfer penalty remain unclear. Wardman (2001) also points out that good shelters, real time information, printed timetables, and good signage are the most important facilities to provide at transfer stations. The CTPS (1997) study addresses the role of some characteristics of the transfer environment, but found that there was inadequate data to assess their impacts on transfers. In this thesis, It is expected that the penalty will vary across the transfer stations.

### 2.2.2 Path Factors

There are two paths: one path involves a transfer, and the other path does not involve a transfer. The former is called the transfer path, and the later the non-transfer path. Both paths have two segments: the first is within the system, and the second is outside the system to the destination. Path factors include in-vehicle time during the system segment, and the environmental factors on the outside segment. The influence of the difference between the two paths in terms of the in-vehicle and environmental factors provide guidance for transfer station location selection, and transit network planning.

### 2.2.3 System Factors

System factors include all the station factors plus in-vehicle time in the transit system. They capture the effects of the system itself on the transfer penalty. The resulting value of the transfer penalty indicates how well the different service lines within the system are connected with each other.

### 2.2.4 Environmental Factors

Studies have shown that urban environmental factors such as land use and urban form can play a significant role in shaping urban mobility and therefore have the potential to offers important potential to influence individual travel behavior. For example, land use may affect travel from the supply side. How land is allocated, composed, and designed has differentiated impacts on the supply quantity, quality and costs of different travel modes. To a transit system, the environment defines its competing modes, and affects the travel behavior after people leave the system, thus influencing the performance of the system. For example, if the service quality provided by the system is poor, while the outside environment is conductive to pedestrian activities, the rider may leave the system early and enjoy walking on the street. However, environmental factors have not been examined in any of the previous studies.

### 2.2.5 Trip and Demographic Factors

In addition to the type of transfer and connectivity, other factors are also expected to affect the size of the transfer penalty. Socioeconomic characteristics such as age, income, and gender often play an important role in travel decisions, and thus the transfer penalty may well vary across these market segments. For example, women and the elderly are generally believed to have a higher transfer penalty than others (Wardman 2001). The availability of car, and the ability to drive are also possible factors which may influence people's willingness to transfer. Income is believed to be a significant variable in determining many aspects of behaviors, and the transfer choice might be no exception. However, all these arguments are largely hypotheses, which have rarely been tested to date.

Trip characteristics include the timing of the trip, trip direction, trip purpose, and trip time. Wardman et *al* reports that commuters have a 29% higher value of wait time than others (Wardman 2001). The transfer penalty is believed to be higher during peak periods than during midday, and higher in the home-work direction than in the work-home direction. However, these remain as beliefs that have never been verified empirically.

### 2.3 Previous Methods

In most transit systems, the transfer penalty is assessed without clear quantitative approaches. The treatment of the transfer penalty in the literature is far from satisfactory. Some transit systems make simple assumptions about the transfer penalty in a subjective way, for example that the transfer penalty equals the transit headway (Liu 1997). Some transit systems use a simple technique to extract the transfer penalty from regional travel models, which are zonally based, aggregate in nature, and generally imprecise (Liu 1998, CTPS 1997).

In addition to the ad hoc treatment of transfer penalties in most transit systems, there are a small number of studies from the academic field but they use different methods and obtain different results. Below is a summary of these studies.

Han (1987) used a binary choice model to test the influence of transfers on bus path choice. The utility function includes waiting time, walking time, in-vehicle time, bus fare, and a transfer dummy. He found that the disutility of one bus-to-bus transfer was perceived to be equivalent to 30 minutes of in-vehicle travel time, or 10 minutes of waiting at a bus stop, or 5 minutes of walk time (Han 1987). He suggests that the values determined from the model indicate that transit planners often underestimate the transfer penalty to bus riders.

Hunt (1990) performed a study centered on the estimation of a logit model of transit route choice behavior using data from commuters in Edmonton, Canada. The model includes such variables as the walking distance to a stop, the wait time for a transfer, and the number of transfers along a given path. He found that the impact of a transfer is equivalent to 17.9 minutes of in-vehicle time, independent of the time spent waiting for the transfer.

Liu (1997) examined modal choice between auto and transit under the impact of transfers. The utility function captures in-vehicle time, out-of-vehicle time, one way cost, and number of transfers. The results show that one transfer is equivalent to approximately eight minutes of in-vehicle travel time or 4.75 minutes of out-of-vehicle travel time. The study found that the value of the transfer penalty was greater than one headway.

A study by Central Transportation Planning Staff (CTPS 1997) estimated the impacts of transfers on urban mode choice in the Boston region using a similar method to Liu's. Variables in the utility function are transfer dummy, in-vehicle time, walking time, waiting time, transfer waiting time, out-of-vehicle time, transit fare, number of workers per household, number of vehicles per worker, and population density. Transfer penalty was found to be equivalent to 12 to 15 minutes of in-vehicle time. Additional findings are that transfer penalties for one or two transfers are similar, and the transfer waiting time is more onerous than initial waiting time.

In summary, all of these studies identify that the presence of a transfer imposes a penalty on the passengers that negatively impacts their willingness to take transit. Various discrete choice models are used to estimate the value of the transfer penalty. However, due to the difficulty of data collection, and data processing, these methods are not widely used in most transit systems in North America. For the same reason, only limited information is provided by previous studies on the magnitude of the transfer penalty. New methods and datasets are needed to further explore the impacts of transfers on travel behavior, which should be easy to use, and more comprehensive in nature. Table 2-2 lists the results from these previous studies.

## 2.4 A New Method

The new method is a combination of on-board survey, partial path choice models, and GIS techniques. On board survey data provides detailed information on transit trips, but is not applicable to traditional modal choice models because of exclusion of non-transit travelers. A partial path choice model allows the on board survey data to be used for discrete choice analysis, but this must be done with the assistance of GIS techniques. GIS techniques allow a disaggregate analysis of the on board survey data, and the choice set of the transfer and the non-transfer options is defined accurately only in a GIS environment. Figure 2-1 shows the structure of this method.

Table 2-2 Previous Transfer Penalty Results

| **Name of the Study** | **Variables in the Utility Function** | **System Studied and Model Choice** | **Transfer Penalty Equivalent** |
|---|---|---|---|
| Han, 1987<br>Taipei, Taiwan | Waiting time<br>Walking time<br>In-vehicle time<br>Bus fare<br>Transfer dummy | Bus, Path Choice | 30 in-vehicle minutes<br>10 waiting minutes<br>5 minutes of walk time |
| Hunt , 1990<br>Edmonton, Canada | Transfer Dummy<br>Walking distance to a stop<br>Wait time<br>Number of transfers along a given route | Rail, Path Choice | 17.9 in-vehicle minutes |
| Liu, 1997<br>New Jersey, NJ | Transfer Dummy<br>In-vehicle time<br>Out-of-vehicle time<br>One way cost<br>Number of transfers | Auto and Transit, Modal Choice | 8 in-vehicle minutes 4.75 out-of-vehicle minutes |
| CTPS, 1997<br>Boston, MA | Transfer dummy<br>In-vehicle time<br>Walking time<br>Waiting time<br>Transfer waiting time<br>Out-of-vehicle time<br>Transit fare | Auto and Transit, Path and Modal Choice | 12 to 15 in-vehicle minutes |
| Wardman, Hine and Stradling, 2001<br>UK | | | 4.5 in-vehicle minutes for bus users<br>8.3 in-vehicle minutes for car users<br>8 in-vehicle minutes for rail users |

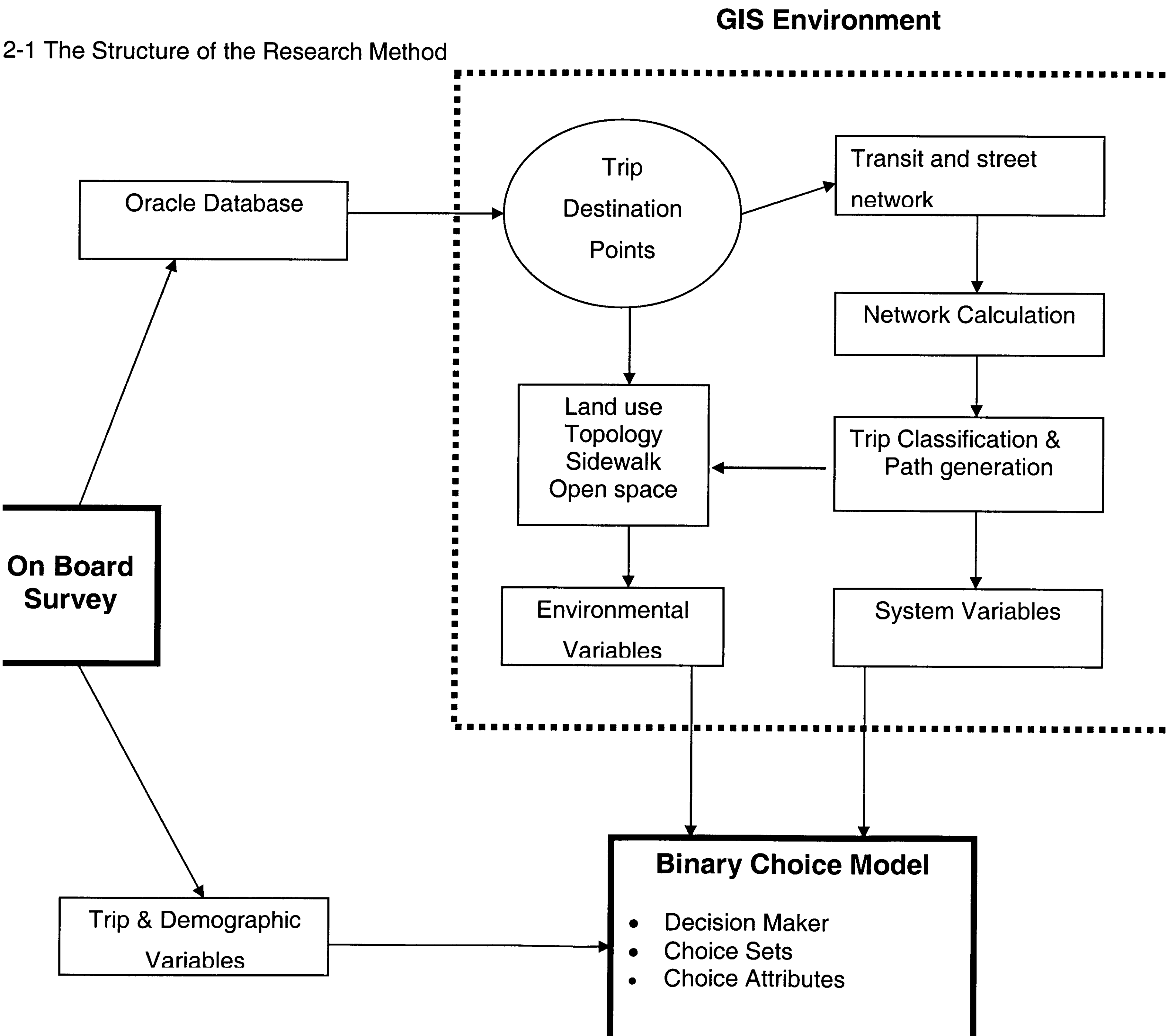
### 2.4.1 A New Data Set

There are two types of data sets used in previous studies. One is the data sets collected specially for the transfer analysis, and the other one is the regional travel diary. Most previous studies used the first type data. In Han's report, he interviewed 1850 bus riders over a two month period, and obtained detailed information from 327 riders on their path choices for a previous trip (Han 1987). In Liu's study, the survey data only provided155 records for model specification. Wardman, et. al use complex stated preference survey data. In total, 242 completed questionnaires were returned from bus users, 132 from rail users, and 182 from car users.

The problem with these data sets is the limited information they can provide due to the intensive data collection effort required and the associated expense. Thus, they only include a small number of variables in the models, and can not provide a comprehensive perspective on the transfer penalty. Their results do not explain the effects on the transfer penalty of station design, network planning, environmental factors, and trip and demographic characteristics.

The 1997 CTPS report is based on the 1991 Household Travel Survey in Boston Metropolitan area. Data were obtained from approximately 3906 households with 38,116 trips, which is quite large and has detailed data on travel modes, trip chains, and demographic characteristics. The CTPS study measures transfer penalty based on both modal choice and path choice. The disadvantages of using this data set are:

2-1 The Structure of the Research Method



1. The data is usually aggregated into large zones, which impairs the accuracy of the resulting assessment.
2. The data does not provide much information on transfer activities.
3. Significant effort is involved in defining path choice between transit and auto trips. The regional model can not precisely define auto paths, and can not calculate the specific path for transit. When comparing the computer-generated paths with the hand coded paths, there are large differences. However, hand coding is extremely onerous, and can only cover a very small portion of all trips included in the analysis.

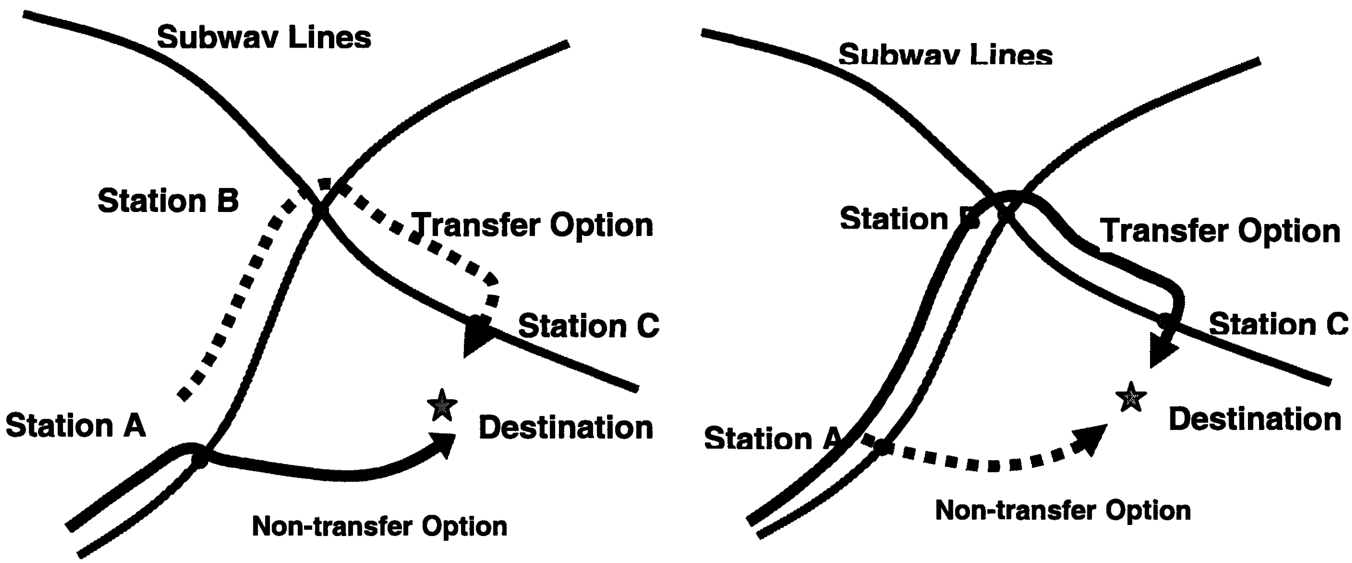
In this research, the data set is the 1994 MBTA On Board Survey for the subway system in the Boston Metropolitan area. The survey is done on a typical week day, and all survey forms are distributed at the entrance of subway stations rather than on the train to avoid a sampling bias towards long trips. It includes more than 38,800 trips, with the origin and destination for each trip, so all trip destinations can be geocoded using GIS software. It also provides information on where people board, transfer, and egress the subway system. The actual transit path can be defined accurately, and all associated characteristics, such as in-vehicle time, transfer time, and waiting time can be calculated accurately. The walking paths to and from transit stops or stations usually cover relatively short distances, and can be predicted more accurately than auto paths. Also this data usually involve the origin and destination locations, which allows disaggregate analysis of the transfer penalty, thus increasing the precision of the results. Since the data only record trips within a transit system, it can not be used to predict the effect of transfers on people's choice to use the transit system. Also traditional modal and path models are not applicable to this data set. A partial path choice model is developed specifically for this data set.

### 2.4.2 A Partial Path Choice Model

Traditional choice models set up choices at the route level. It is assumed that a traveler may change the choice of mode if the route does, or does not involve a transfer. However, in the real world things are not so clear cut. Adding one transfer to a trip may not change the choice to a different route or mode, but only change part of the path. With one more transfer, a traveler may not shift from transit to automobile, but change where, when and how to access/egress the transit system. In summary, transfers not only affect whether travelers choose a particular mode, but also the path for that mode. Transfers not only influence people's choice at the path level, but also at the segment level of the path. For example, a rider may decide to take the subway to get the destination, so the subway mode is taken as given. If the transit trip is divided into a collection portion, main portion, and distribution portion, the rider may have different options to finish the individual portion. The rider may walk, take a bus, or drive to start the trip in the collection portion. The rider may also make a transfer or walk further to finish the distribution portion. This paper will focus on the transfer impact on the distribution portion of a trip, taking the collection and main portion as given.

The basic idea of this method is that some people will choose between 1) leaving the subway line used for the main portion of the trip and walk to the destination, and 2) transferring within the subway system to reduce the walking distance to the destination. Treating the subway system as given, people will face different options during the distribution part of the trip. In the discrete choice model applied, the choice set includes two alternatives: one is to avoid the transfer and walk directly to the destination, and the other is to transfer and then walk to the destination. Figure 2-2 shows the two options. The utility function includes all factors introduced in previous parts of the thesis.

Figure 2-2 Two Options to Get the Destination




### 2.4.3 GIS Techniques

Geographic Information System (GIS) techniques are used extensively in the study. Data are prepared, stored, processed, and displayed in ArcView 3.2, a typical GIS software. There are several major tasks involving GIS techniques.

1. The first task is geocoding. The trip destinations from the on board survey data are geocoded in ArcView 3.2. Trips are represented by points in the GIS map together with a transit system map and a street network map. This provides more accurate estimation of travel paths than with data aggregated at zone level.

2. The second task is network distance calculation. The network distance from the destination to all subway stations are calculated in ArcView 3.2. Based on the distance, trips involving both transfer and non-transfer options are selected. To each destination point, two paths are generated. One is from the destination to the egress station in the non-transfer option, and the other one is to the egress station in the transfer option.

3. The third task is the incorporation of environmental factors. Land use, street network, open space, and topology maps are displayed in the same GIS system, and their values are calculated, and added to both transfer and non-transfer paths of each trip. This involves significant programming.

All the data processed in the GIS environment will enter in a binary logit model for analysis.

### 2.4.4 Limitations of the Method

There are two major limitations of the method. The first is that since the method only deals with people who choose transit, it is unable to measure the transfer's effects on the modal choice between transit and other modes. The second is that since it only focuses on the trips that end in the central city, all trips that end outside this area are excluded even though they might also involve transfer activities. This means that the method only deals with part of all transfer activities within the system. It is also important to know how many trips that involve one or more transfers end outside the central city.

## 2.5 Model Development

Each trip has two options. One is the transfer option, and the other is the non-transfer option. The rider will choose the option that provides a higher utility. The utility associated with each option is determined by the factors described before. The model is developed based on the comparison between the two utilities.

Suppose $U_{in}$ is the total utility associated with option **i** for person N, $U_{in}$ can be written as follows:

$$U_{in} = V_{in} + \varepsilon_{in} \qquad \{ i \in C_n \}$$

Where $C_n$ is the total choice set, $V_{in}$ is the observable or systematic component of the total utility, and $\varepsilon_{in}$ is the unobservable component of the total utility. The choice probability of option **i** is equal to the probability that the utility of option **i**, $U_{in}$, is greater than or equal to the utilities of all other options in the choice set.

$$P(i / C_n) = Pr(U_{in} >= U_{jn}, \text{all } j \in C_n)$$

In this study, we denote the choice set $C_n$ as { i, j}, where, for example, option i is the transfer option, and option j is the non-transfer option. The probability of choosing **i** becomes

$$P_n(i) = Pr(U_{in} >= U_{jn})$$

$$= Pr(\alpha V_{in} + \alpha\varepsilon_{in} >= \alpha V_{jn} + \alpha\varepsilon_{jn}) \quad \text{for any } \alpha > 0$$

Suppose that $\varepsilon_n = \varepsilon_{in} - \varepsilon_{jn}$ is logistically distributed, namely

$$F(\varepsilon_n) = 1 / (1 + e^{-\mu \varepsilon_n}), \quad \mu > 0, \; -\infty < \varepsilon_n < \infty$$

Then

$$P_n(i) = e^{-\mu V_{in}} / (e^{-\mu V_{in}} + e^{-\mu V_{jn}})$$

This is the binary logit model that will be used in this study. The systematic components of the total utility, $V_{in}$, can be written as follows:

$$V_{in} = F(C, S_{in}, E_{in}, K_{in})$$

C: Constant to reflect the difference between option i and j all else being equal

$S_{in}$: System factor variables for option i for person n

$E_{in}$: Environmental Factor variables for option i for person n

$K_{in}$: Trip & Demographic Characteristics for person n

Table 2-3 lists all possible variables that may be included in the utility function.

Table 2-3 Variable list and Data Source

| Type | Variables | Data Availability |
|---|---|---|
| Station Factors | Transfer Walking Time<br>Transfer Waiting Time<br>Change of level<br>Concession | Field survey<br>Extract from headway<br>Field survey<br>Field survey |
| System Factors | Station Factors<br>In-vehicle time | Please see above<br>Data from CTPS |
| Environment Factors | Walking Time<br>Sidewalk width<br>Pedestrian friendly parcels<br>Topology<br>Open Space | Network Distance Calculation<br>MA Highway Department 2003 street Network data<br>MassGIS 1996 Parcel Data Layer<br>MA Highway Department 2003 street Network data<br>Boston Zoning data |
| Path Factor | Environmental Factors<br>In-vehicle time | Please see above<br>Data from CTPS |
| Trip & Demographic characteristics | trip purpose<br>time period<br>trip frequency<br>Fare types<br>Income<br>Gender<br>Occupation<br>Household size<br>License<br>Car ownership | MBTA Subway 1994 survey<br>MBTA Subway 1994 survey<br>MBTA Subway 1994 survey<br>MBTA Subway 1994 survey<br>MBTA Subway 1994 survey<br>MBTA Subway 1994 survey<br>MBTA Subway 1994 survey<br>MBTA Subway 1994 survey<br>MBTA Subway 1994 survey<br>MBTA Subway 1994 survey |
| Note: MBTA Subway 1994 Survey covers four lines (red, green, blue, and orange) with more than 38,000 one-way trip records. | | |

# Chapter 3: Data Processing

Downtown Boston is chosen as the study area because of the concentration of destinations of transit trips in this area, the dense transit network provided, and the unavailability of other modes for rail users besides the subway and walking. Among the total 38,888 trips, about 15,000 destination locations are geocoded. There are 6500 destinations in the study area. These trips are further classified into four types based on whether or not the trip involves a transfer and whether or not the destination is near the boarding line. Only two types of trips that involve both transfer and non-transfer options will be analyzed. Each option is associate with a path. So for each destination, there will be two paths: the transfer path, and the non-transfer path. All factors associated with both paths, such as in-vehicle time, transfer walking time, and transfer waiting time, and environmental factors, will be compared to examine how they affect the transfer choice. So there are three steps in the data processing: trip selection, path calculation, and variable generation.

## 3.1 Study Area and the MBTA Subway System

This thesis focuses on the distribution portion of trips that involve the transfer option. Therefore, trips that end in the Downtown area are the target for analysis because in this area many riders have a transfer option to get close to their destinations. This area also includes destinations of a huge number of trips, more than 6000 trips in this data set, which can provide ample observations for this type of analysis. The downtown area is a high-density built-up area with a good pedestrian environment. There are very few bus lines, and so there are no options for transit riders except for the subway and walking. This reduces the complexity of options that riders may face when they decide whether or not to transfer. The area of Downtown Boston was defined based on both geographical features and transportation network characteristics so that few potential trip paths are cut off by the boundary. The area is bounded by Charles River to the north, Mass Turnpike to the south, Boston harbor to the east, and Massachusetts Avenue to the west.

Four MBTA subway lines run through this area with 21 subway stations. The four transfer stations have a huge number of the transfers everyday, for example, Park Street has over 56,000 daily transfers between the Red Line and the Green Line (MBTA 1997). In fact nearly 25% of all passengers boarding Red Line trains at stations upstream of Park Street, in both south bound and north bound directions, transferred to the Green Line west bound at Park Street (Wong 2000).

Note that Haymarket is treated as a transfer station between Green Line and Orange Line, but North Station is not, because at North Station riders must egress from one station, walk to another station, and pay for entry again. Downtown Crossing is also treated as a transfer station between the Green Line and the Orange Line because there is a direct connection between Downtown Crossing and Park Street. Figure 3-1 shows the study area.

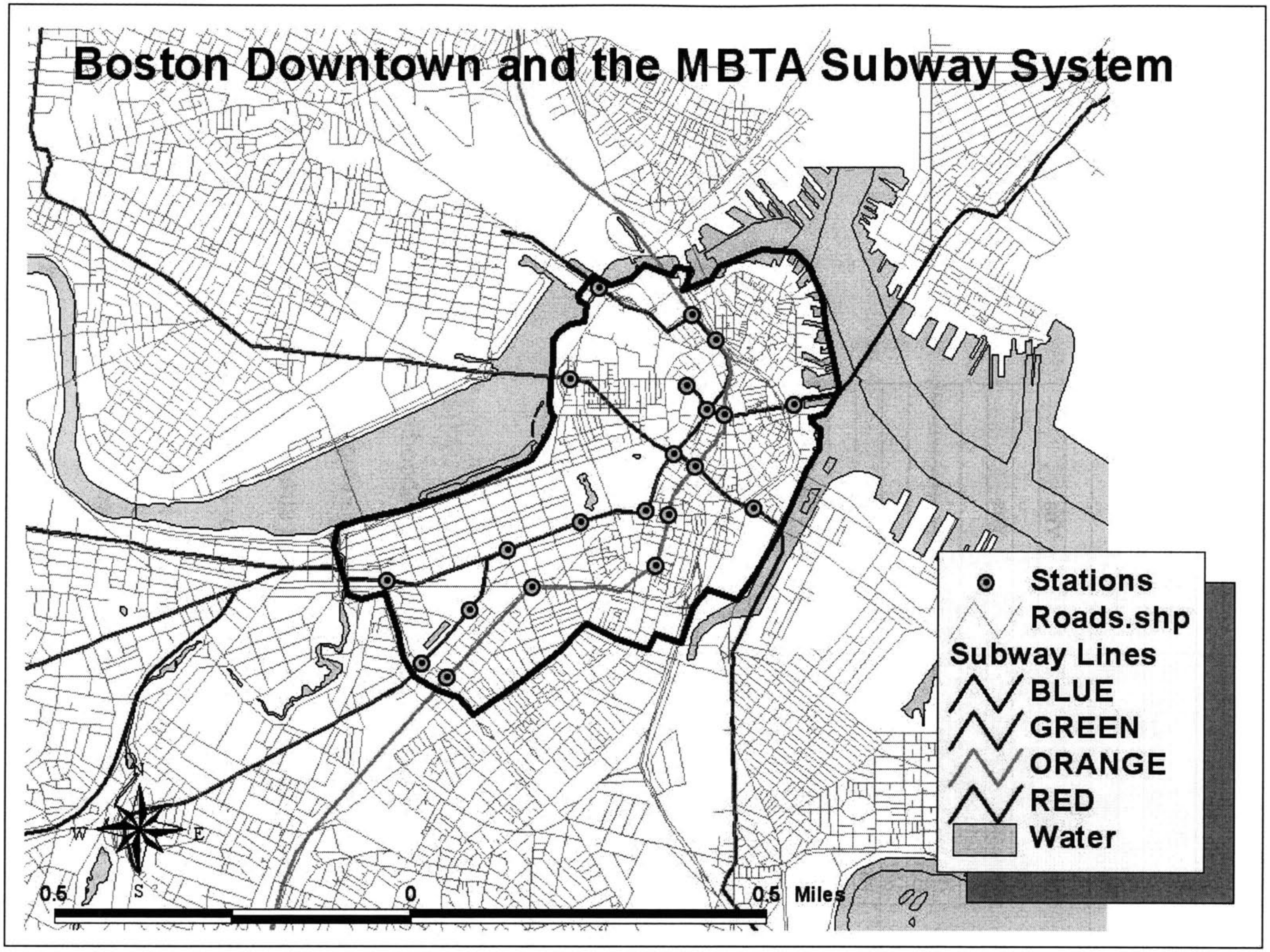



Figure 3-1 The Study Area and the MBTA Subway System

Table 3-1 Subway Lines, Stations, and Transfer Stations in Downtown Boston

| Line | Stations | Transfer Station |
|---|---|---|
| Red Line | Charles/MGH | |
| | Park Street | Yes |
| | Downtown Crossing | Yes |
| | South Station | |
| Blue Line | Bowdoin | |
| | Government Center | Yes |
| | State | |
| | Aquarium | |
| Orange Line | North Station | |
| | Haymarket | Yes |
| | State | |
| | Downtown Crossing | Yes |
| | Chinatown | |
| | NE Medical Center | |
| | Back Bay | |
| | Mass Ave | |
| Green Line | North Station | |
| | Haymarket | Yes |
| | Government Center | Yes |
| | Park Street | Yes |
| | Boylston | |
| | Arlington | |
| | Copley | |
| | Hynes/ICA | |
| | Prodential | |
| | Symphony | |
| Data is obtained from field survey | | |

## 3.2 Geocoding and Trip Selection

### 3.2.1 Geocoding

The first step in processing the survey data is geocoding all destination locations to the street network using ArcView 3.2. All destination locations are recorded as the nearest landmark to the destination, which might be a street mailing address, an intersection of two streets, a name of a store, an institution, or an MBTA station. The data is cleaned before it is entered into ArcView. This is done in Oracle 8.2 with a Lookup table created using SQL/Plus. Errors and misspells are corrected, landmarks are replaced by their street addresses, and different spellings for one address are unified. Zones are added to the address to avoid the miscoding the same street name in different cities. This is a really time consuming work. However, there are still some locations not geocodable because of missing information. After the clean-up, about 15,000 destinations are geocoded to a street network. We assume there is no system bias during the geocoding process.

### 3.2.2 Trip Exclusion

After the geocoding process, there are about 6500 destination points located within the study area representing the same number of trips, but only 1313 locations because some destinations serve multiple trips. The data must be further cleaned as follows before they can be used for the analysis.

Step 1. Egress station must be one of the 21 stations. Otherwise the trip is excluded.

Step 2. Egress mode must be walking. Otherwise the trip is excluded.

Step 3. To simplify the analysis, only one-transfer trips will be considered since it is the case with most trips, and including more than one transfer trips will greatly complicate the analysis. So trips involving both Red Line and Blue Line are excluded from the data set. The number of these excluded trips is only about 40.

Step 4. Transfers among the branches of Green Line are different from other transfers because of the configuration of Green line network. These transfers happen at Copley, which is not designed as a transfer station like the four stations examined in this research. Only 6 trips belong to this group, and these trips also are excluded from the analysis.

After these exclusions, there remain 6269 trips representing1313 unique destination locations. The excluded points are small in numbers and scattered in the downtown area, so I assume there is no bias in the sample points chosen for the analysis. Figure 3-2 shows all the destinations of excluded trips.

### 3.2.3 Trip Classification

Next, all 6269 trips are classified using two criteria: whether or not a trip involves a transfer, and whether or not its destination is closest to the boarding line. So there are four combinations: non-transfer & closest to the boarding line, transfer & closest to the boarding line, non-transfer & not closest to the boarding line, transfer & not closest to the boarding line. I name the four combinations as A, D, C, B respectively. Type B trips involve those who transfer to get close to their destination, and that is what a transfer is all about. In type C, riders prefer walking though they can save walking time by transferring to another line. Type A trips do not have a credible transfer option, since the rider can access the destination from the nearest station without transfer. We expect this is the biggest group of trips. Type D is not rational because the rider transfers but does not egress from the nearest station to the destination. We expect there will be only a few observations in this group. Table 3-2 lists the two criteria and the four combinations. Figure 3-3 shows the options that riders have in each type of trips.

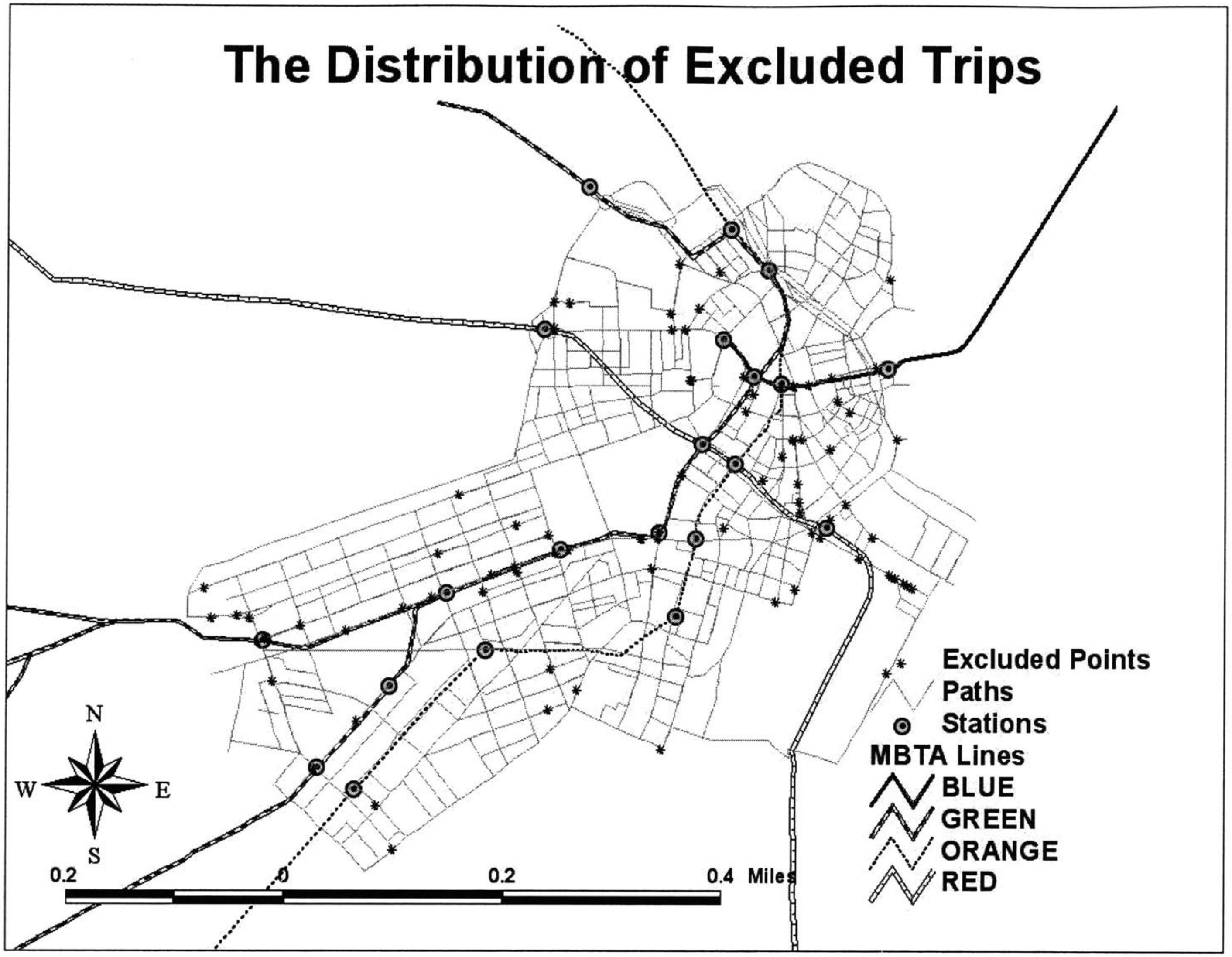
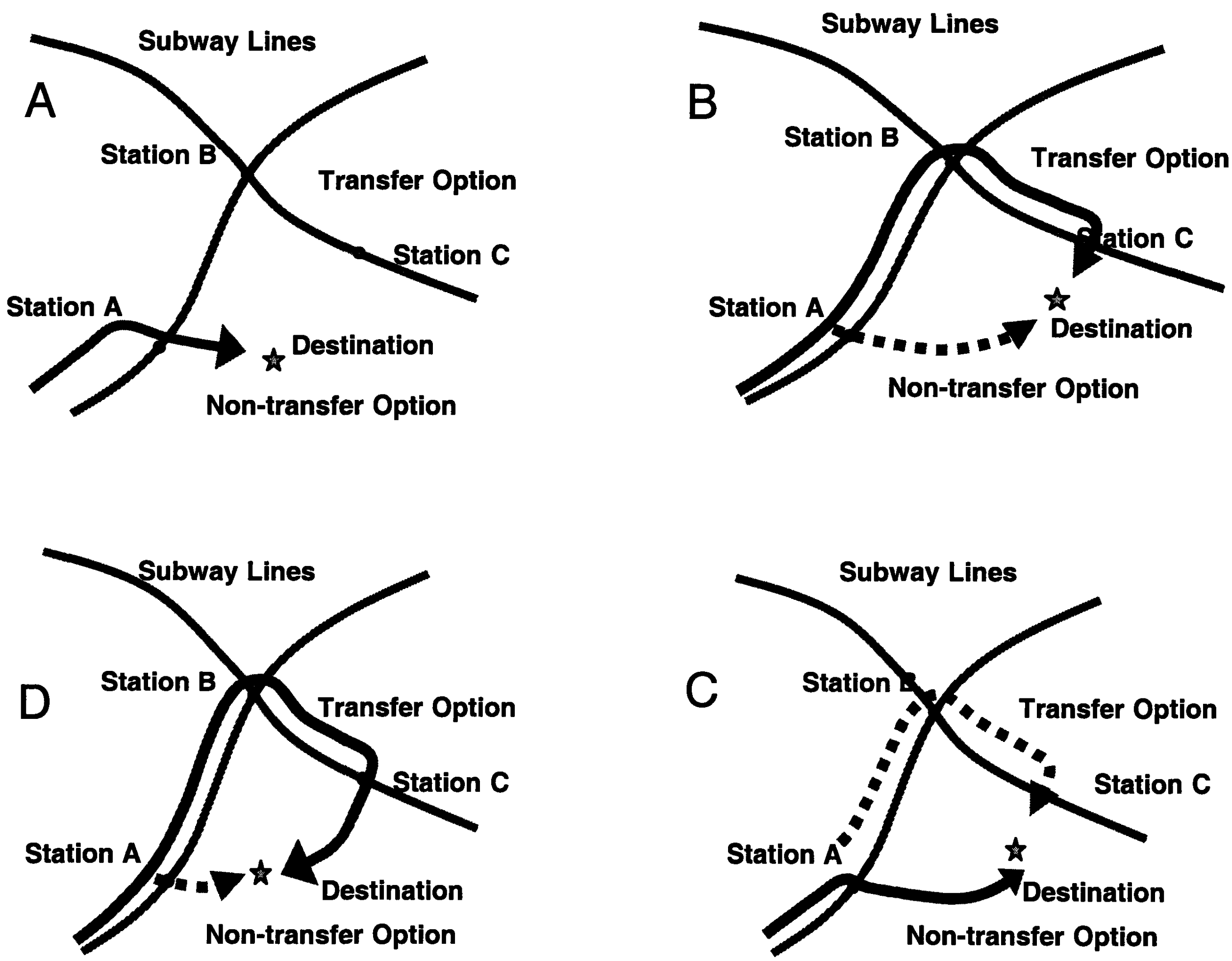



Figure 3-2 The Distribution of Excluded Trips

Table 3-2 Trip Categories Based on Transfer Decision and the Egress Station

| | Closest to Boarding Line | Not Closest to Boarding Line |
|---|---|---|
| **Involves a Transfer** | D | B |
| **Does not Involve a Transfer** | A | C |

Figure 3-3 Four Types of Trips



### 3.2 Path Calculation

#### 3.3.1 Network Distance Calculation

In order to classify each trip among the four types, I need to know the distances between each destination point and two stations. For transfer trips, one station is the egress station, and the other one is the nearest station to the destination on the boarding line. For non-transfer trips, one station is the egress station, and the other one is the nearest station to the destination on any line. The two stations are the same if the non-transfer egress station is in fact the nearest station to the destination. Therefore, three different distances must be compared for each trip to be classified: the distance to the nearest station on any line, the distance to the egress station, and the distance to the nearest station on the boarding line. All distances are network distance and calculated in ArcView 3.x. Figure 3-4 shows the all the paths from each destination to all stations. Refer to Appendix C for detail.

#### 3.3.2 Distance Comparison

The walk network distance is calculated from each of the 1313 destinations to each of the 21 subway stations. The path data is entered into Access and five distances for each destination location are examined: the distance from the destination to the egress station, and the minimum distance to stations on the four subway lines. Then the data is joined back to the destination point shape file as a one-to-many join. Based on the five distances, three numbers are generated for each trip/destination: the minimum distance, the distance to the egress station, and the distance to the nearest station on the boarding line. The minimum distance must be adjusted to exclude double transfers. For example, for all trips on the Red Line, all Blue Line stations except transfer stations are

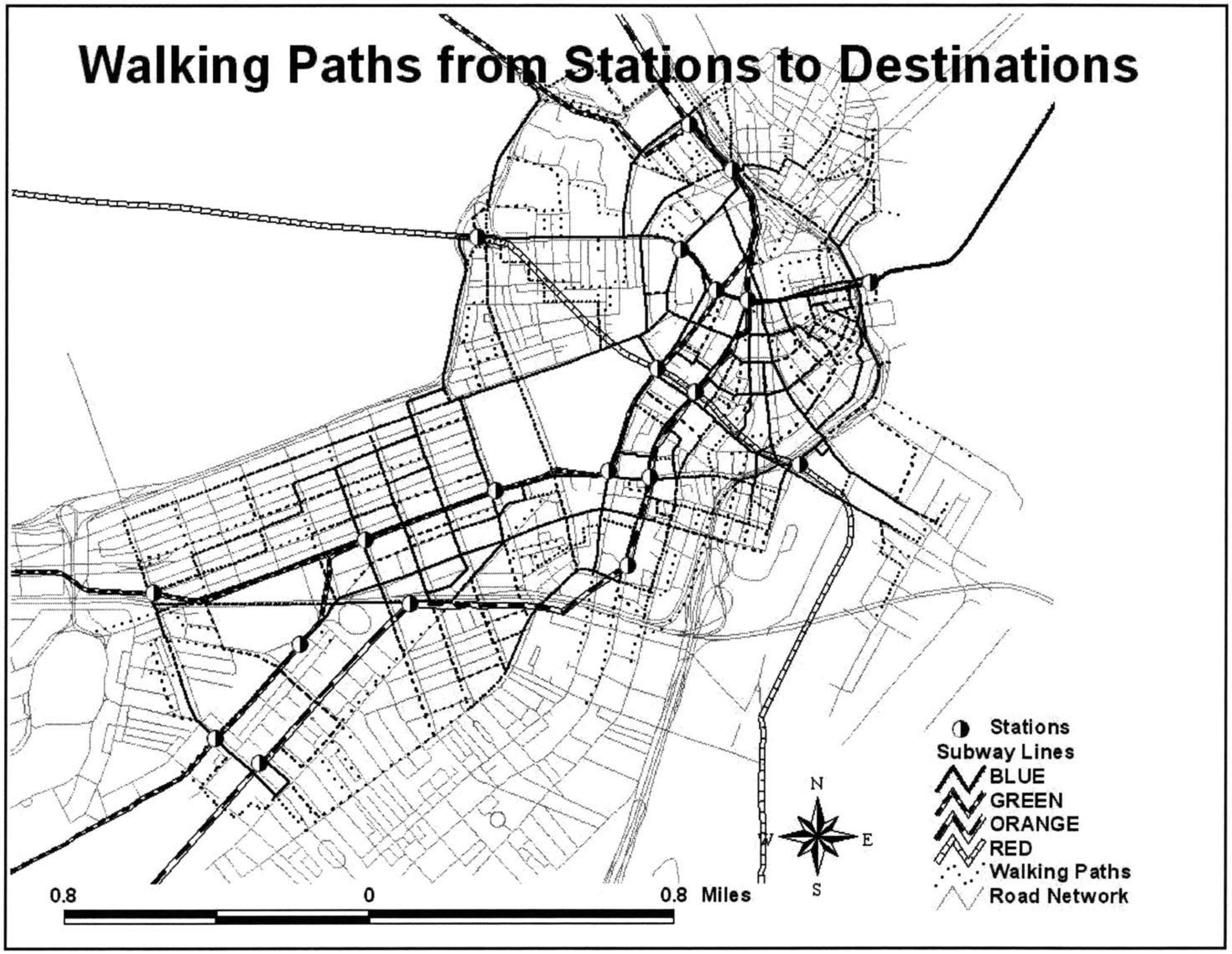



Figure 3-4 Walking Paths from Stations to Destinations

excluded. A similar adjustment is made for the Blue Line. Through the comparison of the three numbers, four trip categories are created. The process is summarized in figure 3-5 and Table 3-3 gives the results of the four categories. As expected, type A is the biggest group with about 40% of total selected trips. 20% are type B trips, and 39% are type C trip. Therefore, when the transfer option is available, about one third of riders choose to transfer in the MBTA subway system. Not surprising, only 5 observations are in type D.

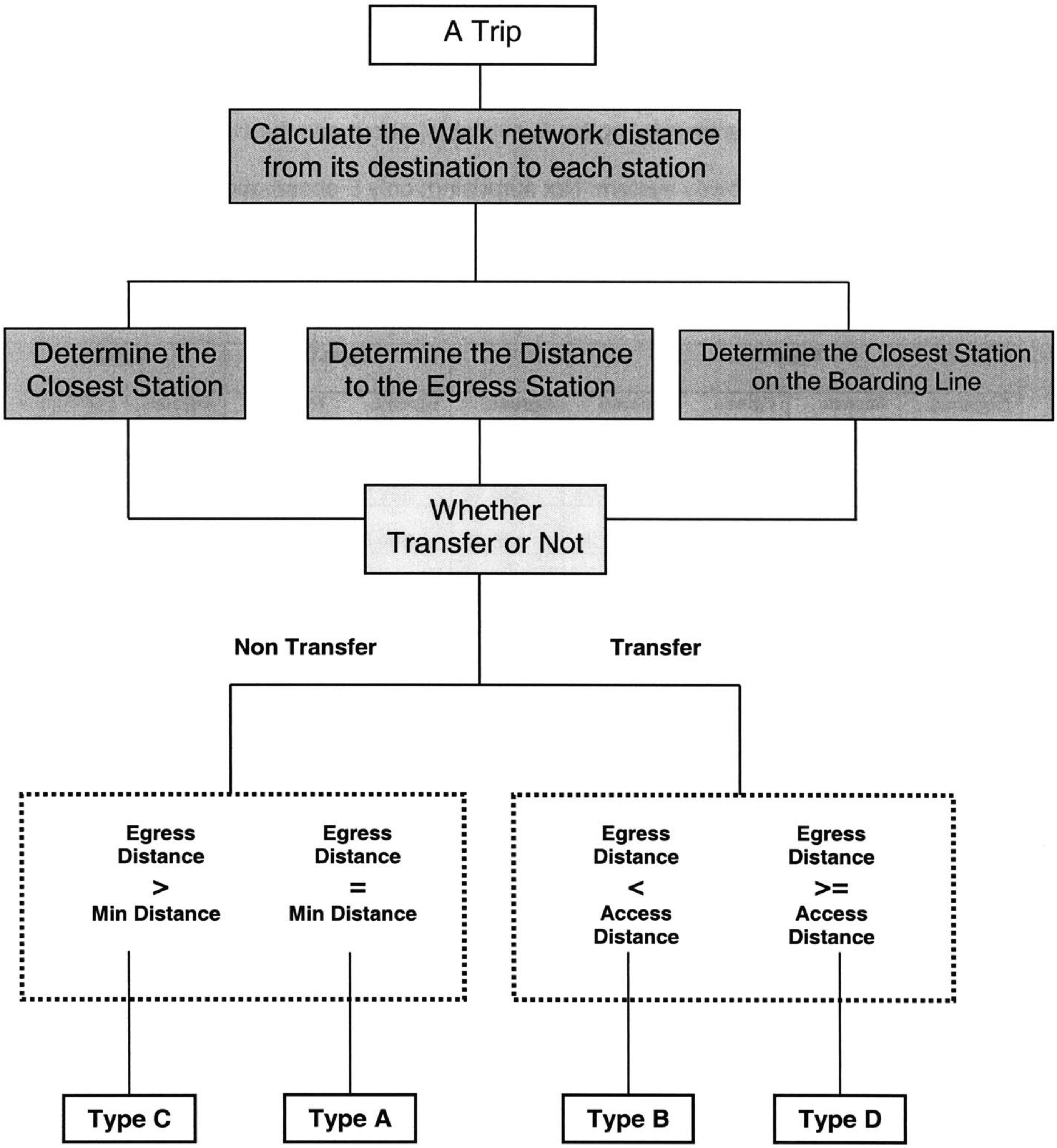
Table 3-3 A Summary of the Walking Distance for the Four Types of Trips

| | **Type D** | | **Type B** | | **Type C** | | **Type A** | |
|---|---|---|---|---|---|---|---|---|
| Distance | **Access Line Distance** | **Egress Distance** | **Access Line Distance** | **Egress Distance** | **Egress Distance** | **Minimum Distance** | **Egress Distance** | **Minimum Distance** |
| **Mean** | 133.72 | 273.44 | 1226.03 | 246.12 | 522.69 | 264.77 | 209.16 | 209.16 |
| **Standard Deviation** | 129.50 | 159.48 | 643.20 | 188.43 | 289.59 | 173.48 | 152.98 | 152.98 |
| **Min** | 40.07 | 42.00 | 183.05 | 0.16 | 1.54 | 1.540 | 0.16 | 0.16 |
| **Max** | 355.60 | 473.73 | 3192.28 | 997.14 | 2442.10 | 1254.21 | 1159.26 | 1159.26 |
| **Total Number** | 5 | | 1313 | | 2428 | | 2523 | |

### 3.3.3 Final Data Set

Type B and Type C trips will be analyzed in the reminder of this thesis. Type D trips are excluded because they are small in number and do not reflect reasonable behavior, and type A trips are also excluded because they do not have a credible transfer option.

Figure 3-5 Trip Classification Process for Each Trip



The result indicates that for type B trips one transfer saves an average walking distance of 980 meters, while giving up one transfer in type C trips only increases the average walking distance by 258 meters. This indicates that on average, one transfer can save 722 meters, or 0.45 miles, of walking distance. This confirms that indeed there is a perceived transfer penalty —people transfer only when they can save a significant amount of time.

Not all the Type B and Type C trips are used for the analysis because two situations must be excluded. For type C trips, when the egress station is not the nearest station even though the nearest station is on the same boarding line. There is still no reasonable transfer option available for this trip, but the rider could have got closer to the destination by egressing without a transfer from another station on the same line. For type B trips, when the egress station is not the nearest to the destination but nearer than the nearest station on the boarding line, there is still a trade off between the walking distance and one transfer. However, this is not the trade off that is explained only in terms of distance traveled. All trips with these characteristics are excluded. The final data set includes 3145 trips with 1123 transfer trips, and 2022 non-transfer trips. Figure 3-6, 3-7, 3-8 show the destinations for the excluded trips, and for the final set of transfer and non-transfer trips.

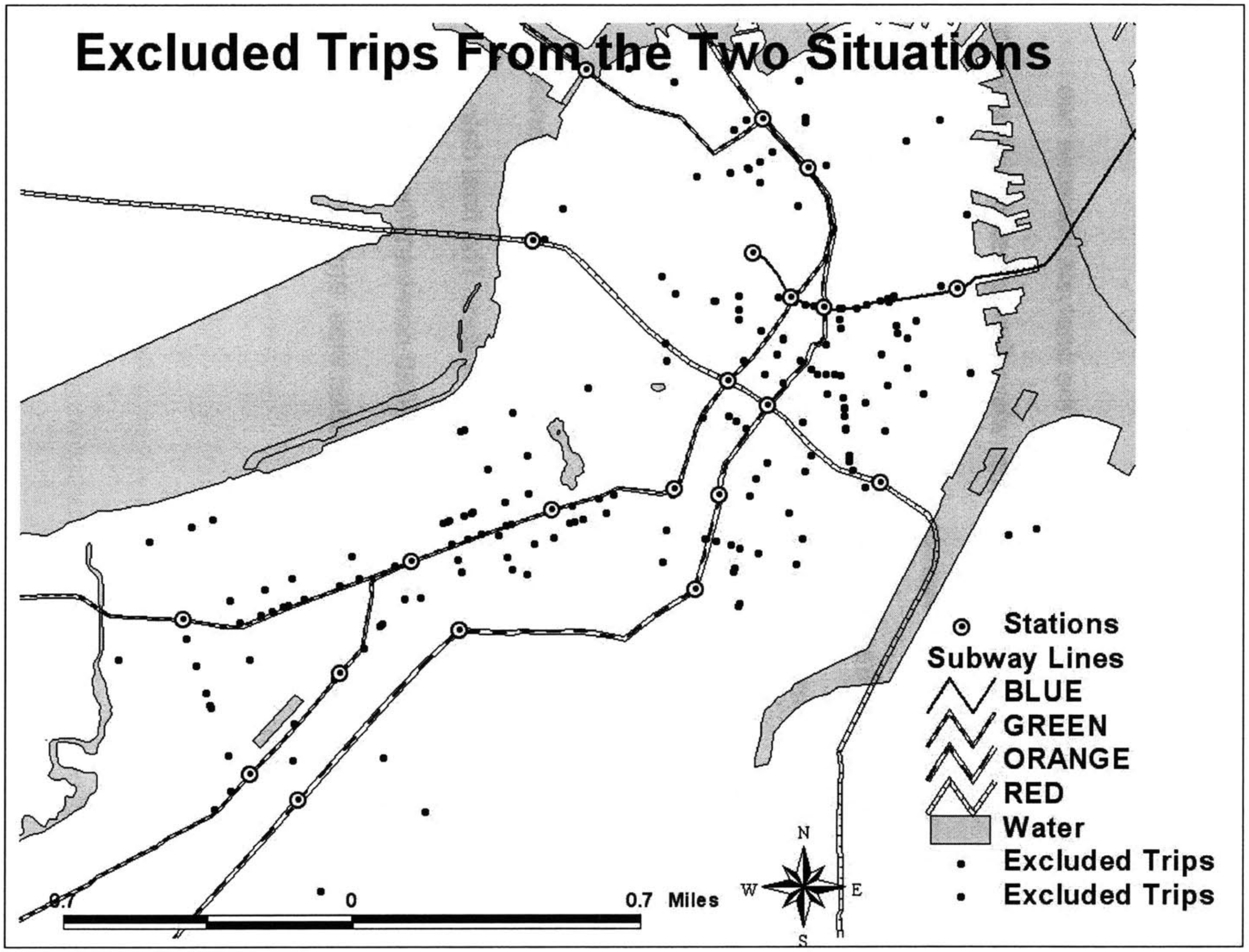



Figure 3-6 The Excluded Trips from the Two Adjustment

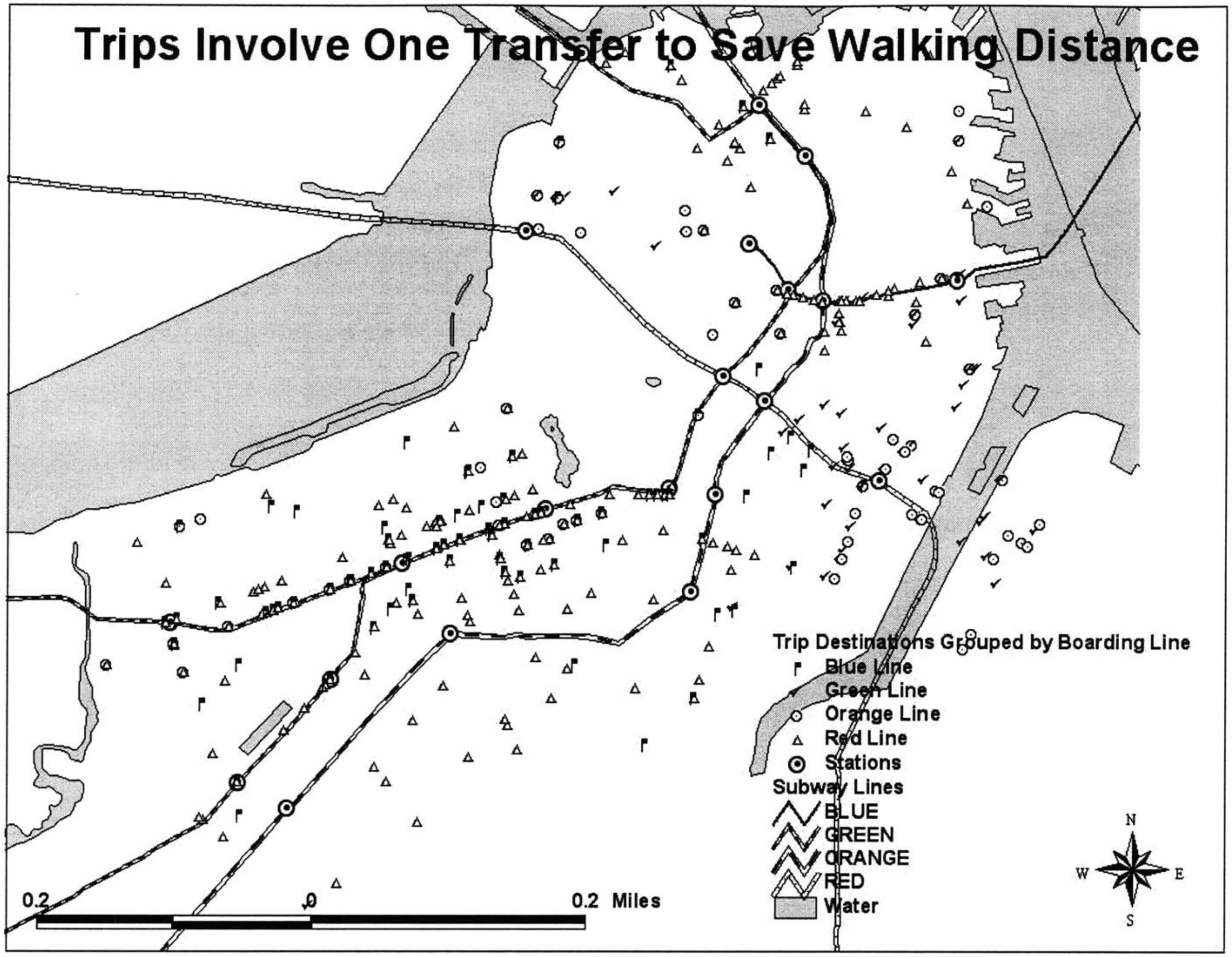



Figure 3-7 Trips Involve one Transfer to Save Walking Time

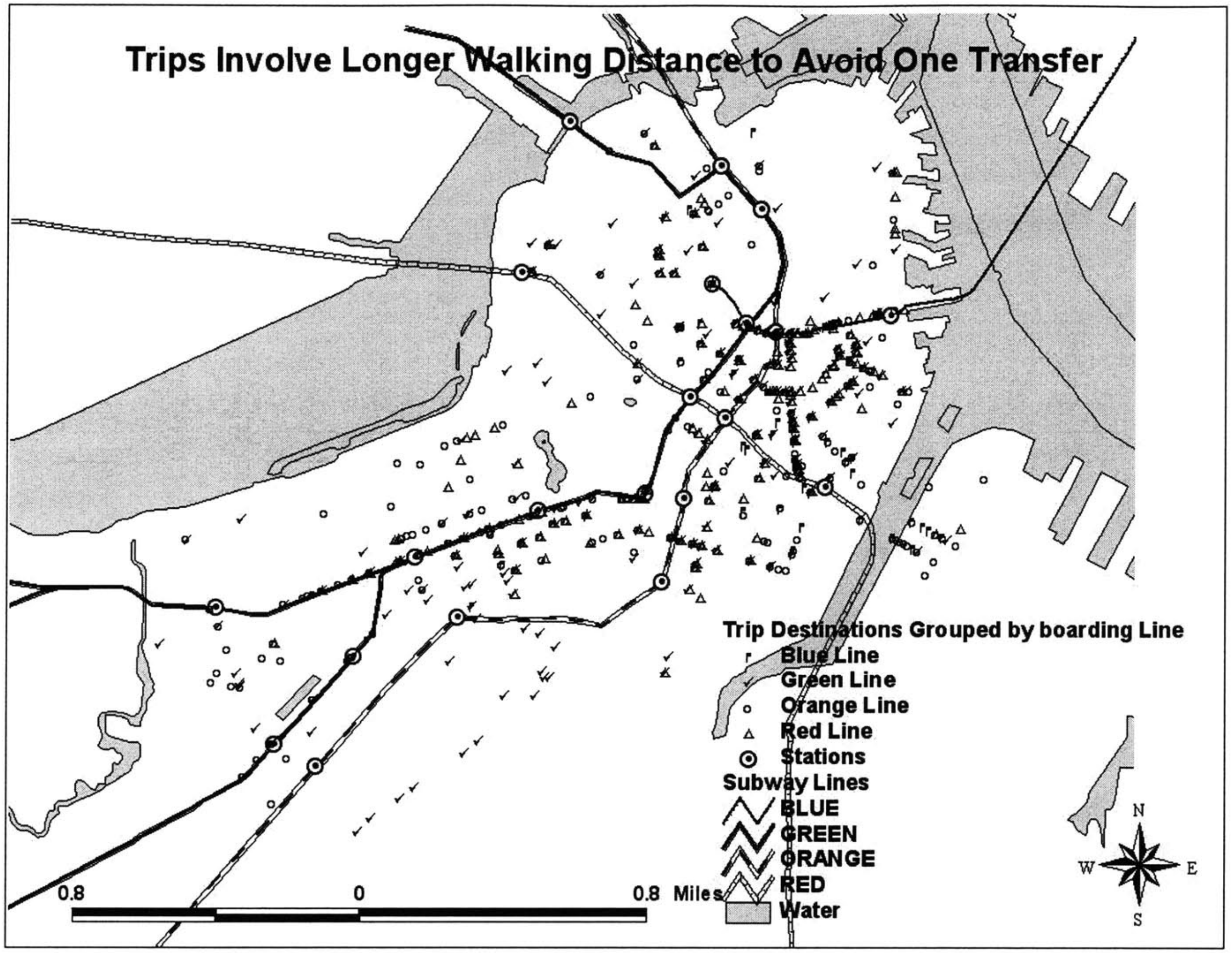



Figure 3-8 Trips Involving Longer Walking Distance to Avoid One Transfer

### 3.3.4 Two Paths

If a trip involves a transfer, it is a transfer trip, otherwise it is a non-transfer trip. However, no matter whether or not a trip is a transfer trip, there are two options available: the transfer option and the non-transfer option. Each option is associated with a walking path to the destination. I call the walking path of the transfer option a transfer walking path, and that of the non-transfer option a non-transfer walking path. To make it clear, a transfer trip has both a transfer walking path and a non-transfer walking path available, but the transfer path was selected. Similarly, a non-transfer trip also has the two paths available, but the non-transfer path is selected. All variables are created for both paths of each trip, and the comparison can then be made to determine which option has a higher utility to the rider.

## 3.4 Variable Generation I: Station Variables

Station variables are factors that only exist within transfer stations, which may affect the transfer penalty. They include time variables such as transfer walking time and transfer waiting time and facility variables such as change of level and availability of concessions.

### 3.4.1 Transfer Walking Time

Transfer walking time is the walking time from the transfer arrival platform to the transfer departure platform. Transfer time varies across different lines and different directions on these lines. For example, there are four different transfers between the Orange Line and the Red Line: south bound Red Line to north bound Orange Line, south bound Red Line to south bound Orange Line, north bound Red Line to north bound Orange Line, and north bound Red Line to south bound Orange Line. Table 3-4 shows the estimated transfer waiting times for all possible transfer movements based on field surveys by the author.

Table 3-4 Transfer Walking Times

| From \ To | | Red Line | | Orange Line | | Green Line | | Blue Line | |
|---|---|---|---|---|---|---|---|---|---|
| | | South | North | South | North | East | West | West | East |
| **Green Line** | West | 17 | 14 | 31 | 50 | | | 20 | 20 |
| | East | 17 | 14 | 31 | 50 | | | 20 | 20 |
| **Orange Line** | South | 60 | 56 | | | 117 | 117 | 130 | 116 |
| | North | 50 | 57 | | | 217 | 217 | 32 | 30 |
| **Red Line** | South | | | 60 | 54 | 17 | 14 | | |
| | North | | | 56 | 57 | 17 | 14 | | |
| **Blue Line** | West | | | 130 | 32 | 20 | 20 | | |
| | East | | | 116 | 30 | 20 | 20 | | |
| All times are in seconds | | | | | | | | | |

### 3.4.2 Transfer Waiting Time

Transfer waiting time refers to the time that a traveler waits at the platform to make the transfer trip. It is calculated as half the headway of the subway line. For the Red Line, the headway estimate is the combined headway of both Braintree and Ashmont trains. For the Green Line, it is the combined headway of B, C, D, and E lines. Therefore, the headway of the Green Line at different downtown stations can be different: specifically Haymarket has longer headways than Government Center or Park since not all trains go to Lechmere. Similarly, the Hynes Convention Center has a longer headway than the downstream stations on the Green Line after Copley because the E line does not serve it. Table 3-5 lists the estimated waiting time for the four lines. The headway data is obtained from the MBTA website.

Table 3-5 Transfer Waiting Times of the MBTA Subway in Downtown Boston

| Line | Waiting Time | Transfer Stations |
|---|---|---|
| Red Line | 224 | Park and Downtown Crossing |
| Orange Line | 300 | State and Downtown Crossing |
| Blue Line | 240 | State and Government Center |
| Green Line I | 89 | Park and Government Center |
| Green Line III | 540 | Haymarket |
| All times is in seconds | | |

### 3.4.3 Transfer Facility

Transfer facility may affect the transfer penalty through the general condition of a transfer station, the layout of platforms, the design of stations, and available opportunities. In this research, I choose two factors in the analysis: the existence of a concession on the transfer platform, and the need to change platform levels between arrival and departure locations (Crockett 2001). The existence of concessions is believed to ease the discomfort and anxiety during transfers, and make the transfer waiting time more pleasant, thus reducing the transfer penalty. The change of level refers to whether the transfer involves changing levels. In the MBTA subway system, the change of level usually involves one floor difference, and there are three ways to accomplish this change: stairs, escalator, and elevator. In some stations, one way escalators are provided to help riders to change levels, however, they may not work all the time. Elevators are often used by travelers with disabilities. In this research, I did not classify the change of level variable at a finer level of detail.

If two subway lines intersect with each other, a change of level is always required to transfer between the lines is performed. In the field survey, I found that all the transfers involved a change of level, except those between the East bound Blue Line and the South bound Orange Line, and between the West bound Blue Line and the North bound Orange Line, which only involve a few stairs. So these trips only are defined as having no change of level. Concessions are provided on the East bound Green Line platform at Park, both directions of the Green Line platform at Government Center, both directions of the Blue Line at State, and the South bound platform of the Orange Line at Downtown Crossing. (See appendix for the summary of the change of level and concessions at all transfer stations. )

### 3.5 Variable Generation II: Path Variables

Path variables refer to those factors within the transit system, but outside transfer stations that may affect the transfer penalty. There are two major variables: in-vehicle time spent in the transit system, and walking time spent between the system stops and the trip destinations.

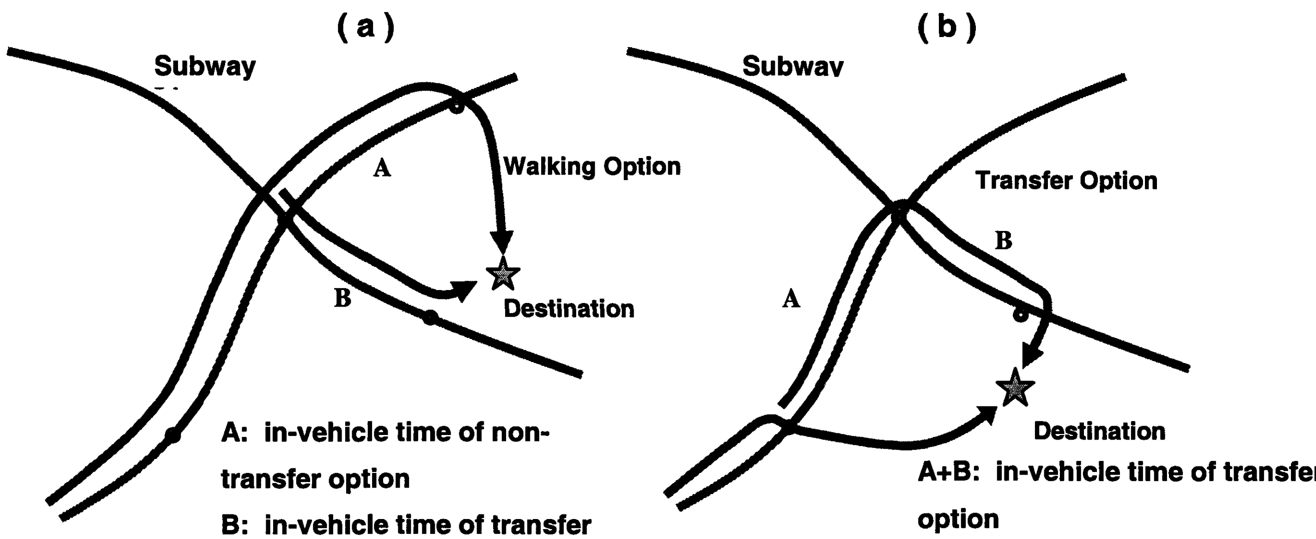
### 3.5.1 Walking Time

Walking time refers to the time from the egress station to the trip destination. For each destination the walking time is estimated for both the transfer and non-transfer paths based on the network distance and assuming a normal walking speed of 3 miles per hour. We assume that riders are indifferent between a minute of walking time on the transfer and non-transfer path. Therefore, the two walking times share the same coefficient in the model. Their difference, on the walking time savings is calculated as non-transfer walking time minus transfer walking, and will enter into the model in this form.

### 3.5.2 In-Vehicle Time

In-vehicle time refers to the time spent in the subway system. We are only concerned with the difference in in-vehicle time between the transfer and non-transfer options, and so we use the extra in-vehicle time involved in the transfer option in the model specification. The extra in-vehicle time is defined as transfer in-vehicle time minus non-transfer in-vehicle time. Note that the non-transfer option can have a longer in-vehicle time than the transfer option when the non-transfer egress station is further from the transfer station than the transfer egress station. For example, in figure 3-9, if the rider chooses not to transfer, the nearest station to the destination on the boarding line is the next stop after the transfer station taking in-vehicle travel time A after the transfer station. However, if (s)he transfers, the rider will travel time B before exiting the system. Time A may be longer than time B. In this case, the "extra" in-vehicle time will be negative. In most cases, however, it will be positive as shown in figure 3-9.

Figure 3-9 Two Types of In-vehicle Time for the Non-transfer Option of Each Trip




Among the 1123 transfer trips, 206 trips are as shown in figure 3-9 (a) as well as 471 trips among the 2022 non-transfer trips. Because even in this situation, time A can be less than time B, the number of trips with negative extra in-vehicle time will be less than 206 + 471 =677. Actually, there are only199 trips with a negative extra in-vehicle time in the data set.

### 3.6 Variable Generation III: Environmental Variables

Because the competing mode to the subway system in Downtown Boston is walking, and the walking mode is largely affected by pedestrian environment, environmental factors along the walking path are expected to influence riders choice to transfer, thus may affect the transfer penalty. Pedestrian environment can be described by many variables. In this study, I only include four variables: pedestrian friendly parcels, sidewalk width, open space, and topology, which are assumed to be the most important factors.

### 3.6.1 Pedestrian Friendly Parcels (PFP)

Adjacent land use affects the perceptions of pedestrians. Retail, commerce, and mixed development are believed to be more conductive to pedestrian activities than industrial, residential, and office land use. If there are more stores, restaurants, clubs etc along a particular walking path, people may prefer that choice. Empirical evidence also indicates that people are willing to walk longer distances along Bolyston Street, which has multiple activities and walking amenity. In this study, the land use influence is defined by the total number of Pedestrian-Friendly Parcels (PFP) along the walking path. PFPs refer to the parcels that can stimulate pedestrian activities. In the Boston 1996 Assessor database, about 97 parcel types are chosen from more than 300 parcel types as PFPs, which primarily include mixed use, retail, recreation, food and other services. Figure 3-10 shows all PFPS in Downtown Boston. (see Appendix for detail of all type of PFPs).

In this research, I use the density of PFPs rather than the absolute number of PFPs along the walking paths for both transfer and non-transfer options to avoid the length effect of the paths. The density of PFPs is defined as the total number of PFPs along the walking path divided by the length of the path in units of100 meters. Because we are only concerned with the difference of this density between transfer and non-transfer paths, I use the difference of the density as the variable for analysis. The difference is calculated by subtracting the density of PFPs on the transfer path from the density of PFPs on the non-transfer path, which shows how many extra PFPs per 100 meters there are along the non-transfer walking path compared with the transfer walking path.

### 3.6.2 Sidewalk Width

While many characteristics of the street network, such as number of lanes, speed limits, curbs, sidewalk width, traffic lights, shoulder width etc. may affect pedestrian activities, most of these features do not vary much in Downtown Boston. However, sidewalk width does vary and may have a significant impact on pedestrian activities, and so only sidewalk width is included in the analysis. It is the average width of sidewalk along the walking paths. It is measured as the total sidewalk area divided by the total length of the walking path. Because we are only concerned with the difference of this value between the transfer and non-transfer options, a variable is created by subtracting the average sidewalk width of the transfer path from that of the non-transfer path. The sidewalk data is obtained from Massachusetts Highway Department. The data is joined to the street network in ArcView, so sidewalk width can be assigned to the two paths. Figure 3-11 shows the average sidewalk width in Downtown Boston. ( see Appendix C for the detailed calculation method. )

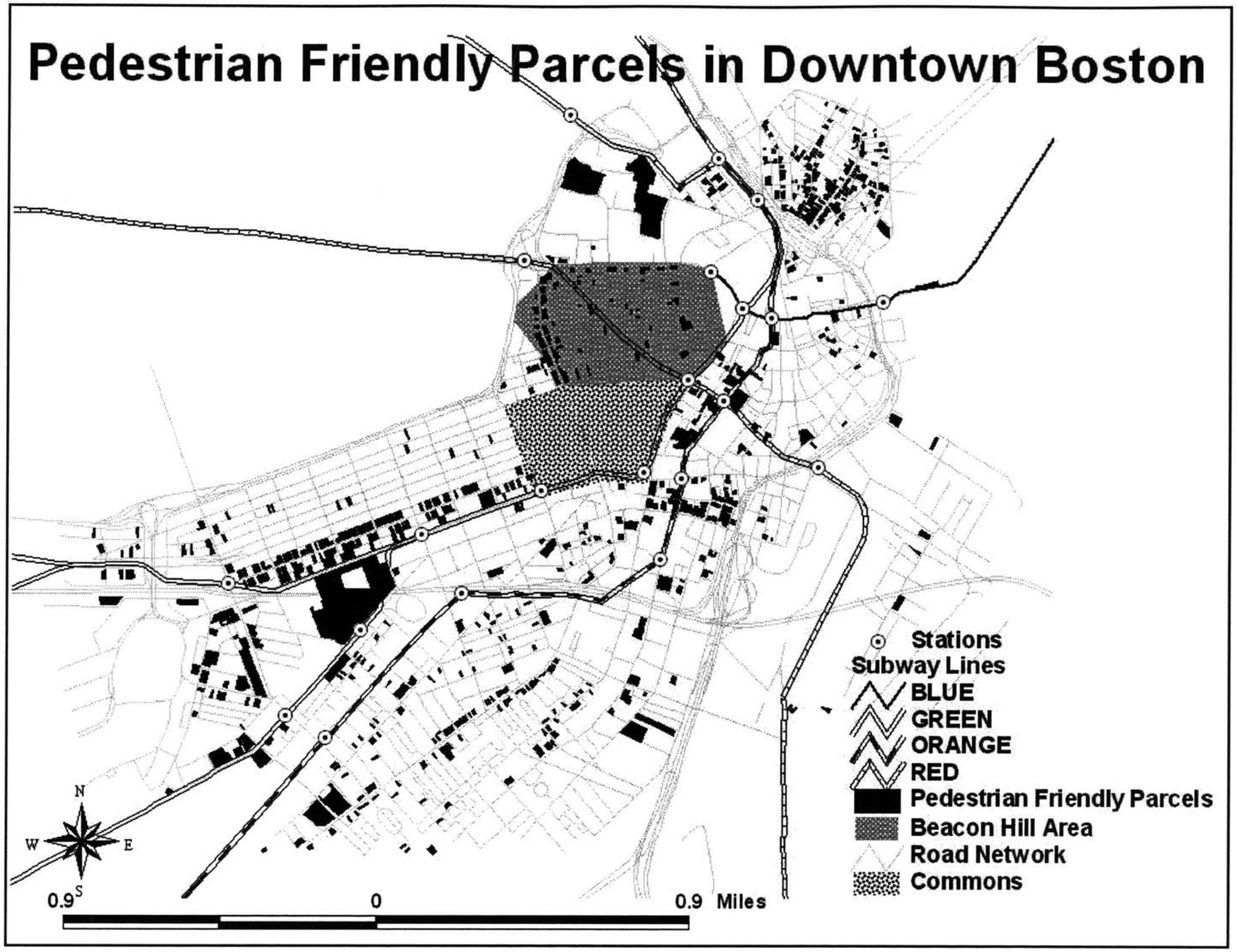



Figure 3-10 Pedestrian Friendly Parcels, Beacon Hill, and Boston Common in Downtown Boston

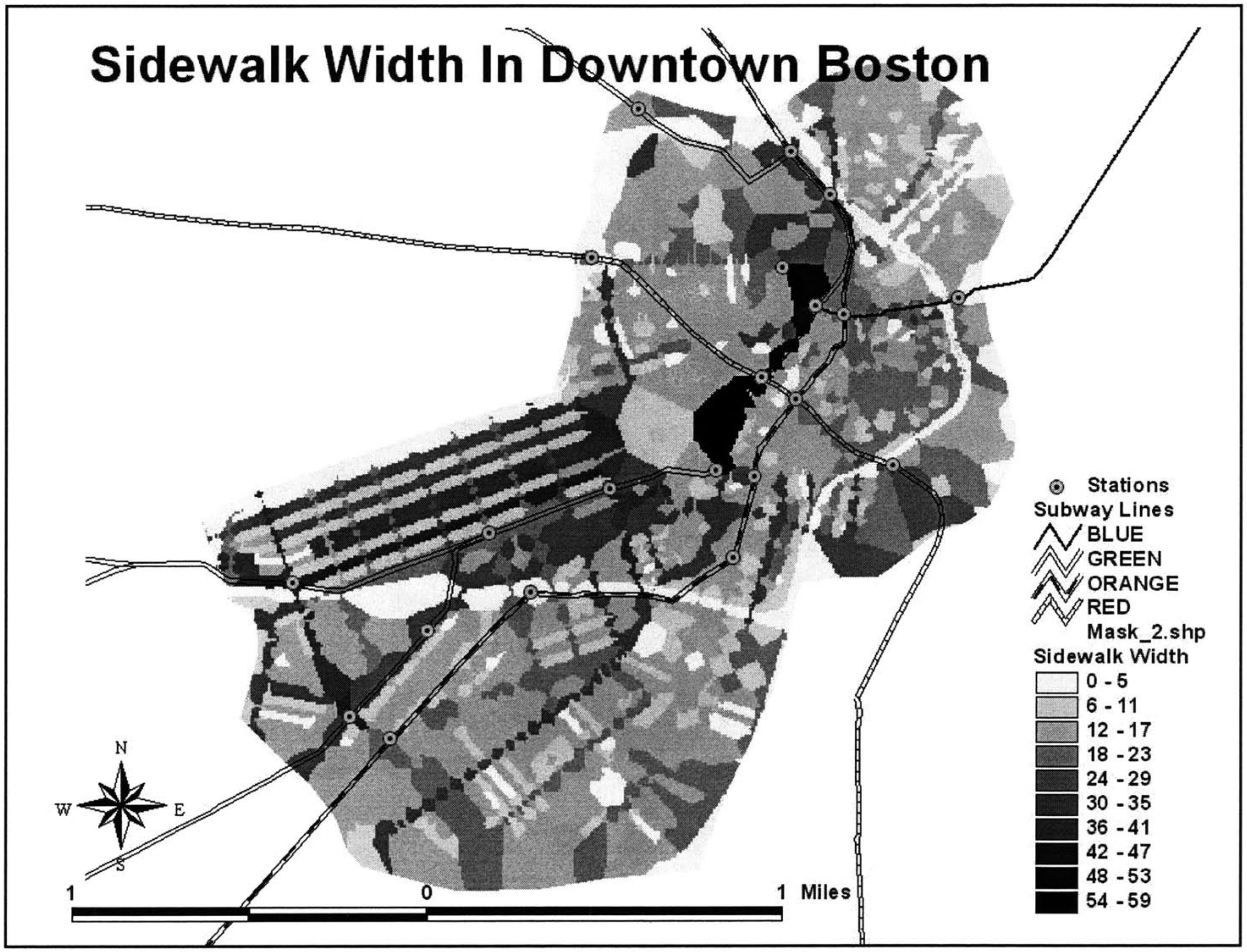



Figure 3-11 Average Sidewalk Width in Downtown Boston (in feet)

### 3.6.3 Open Space and Topology

Adjacent open space like parks, play-grounds, or water bodies, may be conducive to pedestrian activities. Specifically, Boston Common, which is located near Park Street Station, might affect the transfer decision for some trips. Based on whether or not the transfer and non-transfer path run through the Common, there are four combinations as listed in Table 3-6. Because we want to check the effect of Boston Common, combination 1 is chosen as the base leaving three dummy variables. Because dummy1 only has a small number of observations, we may exclude it in the model specification. So two dummy variables will enter into the model. Dummy2 is 1 when the transfer path run through Boston Common while the non-transfer path does not. Otherwise it is zero. Dummy3 is 1 when both transfer and non-transfer paths run through Boston Common, otherwise it is zero.

Table 3-6 Dummy Variables for Open Space

| | **Transfer Path** | **Non-transfer Path** | **Variable** | **Observations** |
|---|---|---|---|---|
| **Combination 1** | Not Through Common | Not Through Common | Base | 1871 |
| **Combination 2** | Through Common | Not Through Common | Dummy1 | 88 |
| **Combination 3** | Not Through Common | Through Common | Dummy2 | 867 |
| **Combination 4** | Through Common | Through Common | Dummy3 | 322 |

People do not like walking in hilly topology because it is more difficult. Downtown Boston has hilly topology in Beacon Hill as defined by MassGIS, which may influence people's choice of path: people may tend to avoid walking in hilly terrain. There are also four combinations based on whether or not the transfer path or non-transfer path runs through Beacon Hill as listed in Table 3-7. Since we want to check the effects of hilly topology, combination 1 is used as the base. There are three dummy variables. Because dummy1 and dummy3 only have a few number of observations, we only include the second dummy variables in the analysis. Dummy2 is 1 when the non-transfer path runs through Beacon Hill while the transfer path does not. Otherwise it is zero.

Table 3-7

| | **Transfer Path** | **Non-transfer Path** | **Variable** | **Observations** |
|---|---|---|---|---|
| **Combination 1** | Not Through Beacon Hill | Not Through Beacon Hill | Base | 2033 |
| **Combination 2** | Through Beacon Hill | Not Through Beacon Hill | Dummy1 | 20 |
| **Combination 3** | Not Through Beacon Hill | Through Beacon Hill | Dummy2 | 1087 |
| **Combination 4** | Through Beacon Hill | Through Beacon Hill | Dummy3 | 70 |

### 3.7 Variable Generation IV: Trip and Demographic Variables

Trip variables include trip time, trip purpose, trip frequency, and fare type. Trip time is the time when the trip begins: morning peak from 6:00am to 8:45am, morning from 8:45am to 11:45am, and afternoon from 11:45am to 3:00pm. Trip purpose refers to the activities that the traveler will perform at the destination including work, home, school, personal business, shopping, and social or recreational activity. Trip frequency has two types of variables: the number of days per week the traveler uses the subway system per week, and the number of subway trips on that day. Fare types include cash/token, monthly pass, and others, such as 10-Ride ticket, reduced fares, and visitor passport. Trip variables may affect the transfer penalty, but this has rarely been verified in past studies. In the next chapter, I will test the trip variables in model specifications to see if there is an effect, and if so, which factors affect the transfer penalty.

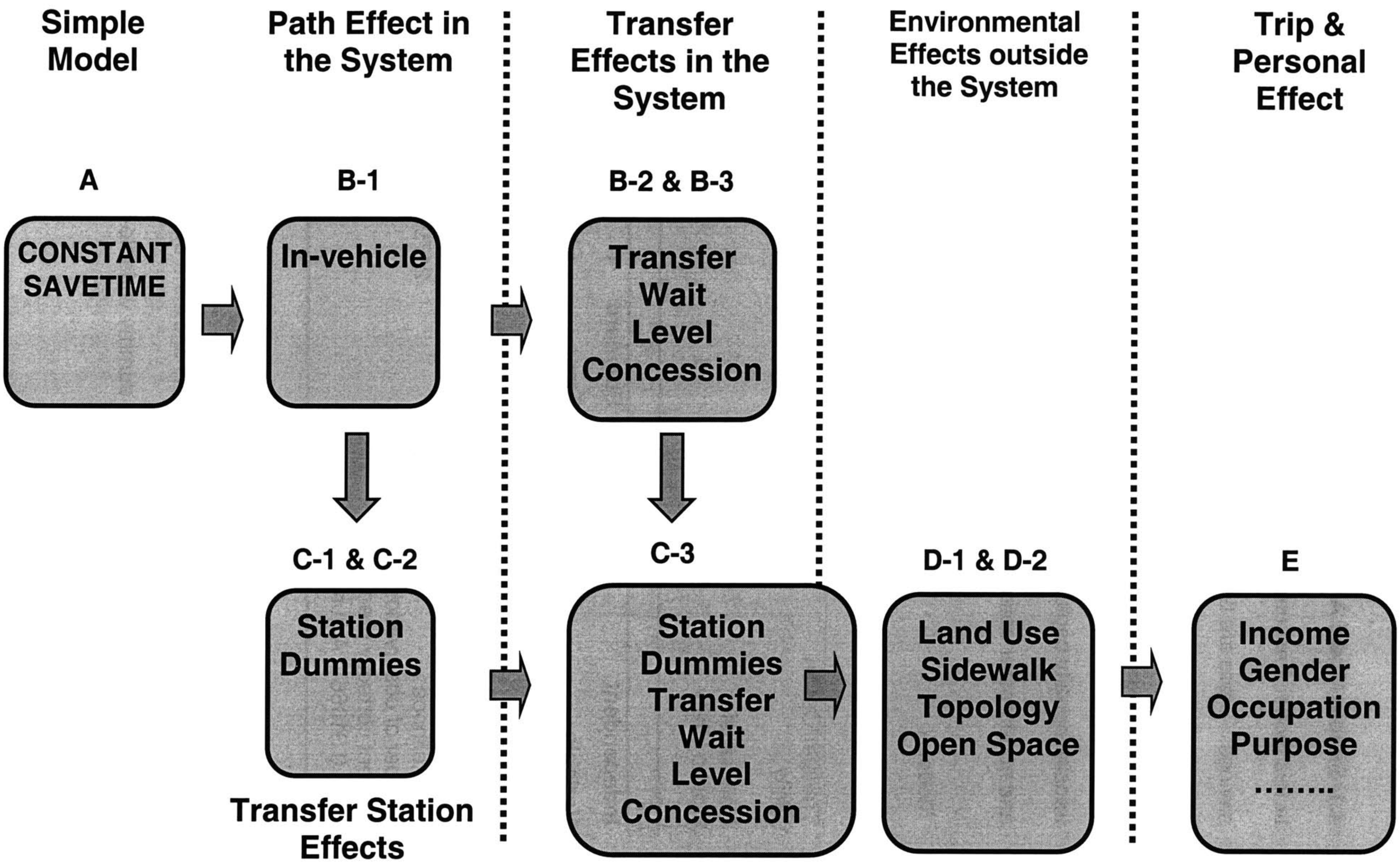
Demographic characteristics may also influence people's decision on whether or not to transfer. Some empirical findings support this argument. For example, in analyzing the statistics from the MBTA survey, those under 18 years of age are more likely to transfer than other age groups (30% vs. 20%), and people without a vehicle are more likely to transfer (24% vs 17%). However, as with trip variables, this remains a supposition which has not been verified statistically. This research will test this assumption, and examine to what extent the effect exists. The demographic variables include age, license, auto availability, occupation, gender, household size, income, and number of cars owned.

These are all the variables that will enter into the model specification. A statistical summary of all the variables is given in Appendix A.

# Chapter 4 Model Specification and Interpretation

In this chapter, a series of models will be presented. First, I will start with the simplest model with only a transfer dummy and the walking time savings variable. This model does not attempt to explain choices in terms of the various factors mentioned before, but collapse all effects into a single transfer penalty: the total transfer penalty. Next, models are developed in two directions. In the first direction, path and transfer station attributes are added. The penalty reflected in the transfer dummy variable will decrease because these new factors will also capture part of the penalty. In the second direction, transfer station dummies are added to examine the variation of the transfer penalty across the four transfer stations. Path and station attributes are also added later in this direction to test their effects on specific stations in terms of the transfer penalty. Then, the best model specification from the two directions is chosen, which describe the transit system effect on the transfer penalty. Based on the best specification, environmental variables are added to test their effects on the transfer penalty. The assumption behind this test is that the penalty is affected not only by the subway system, but also by the outside urban environment. Last, trip and personal characteristics are also examined to see if they have a significant impact on the transfer penalty. There are a total of 10 model specifications. Figure 4-1 shows the sequence of the model development.

Figure 4-1 The Structure of Model Development



### 4.1 Simple Model A

In this model, I assume that the utility function includes only the walking time savings. There are two variables in the model: a transfer dummy, and the walking time savings. If both coefficients are significant, their ratio represents the equivalence between one transfer and walking time saved. This is the total transfer penalty capturing the effects of all the differences between the transfer and non-transfer options except the walking time savings.

Model A

| | $\beta_1$ | $\beta_2$ |
|---|---|---|
| Transfer Option Utility | 1 | Walking Time Savings |
| Non-transfer Option Utility | 0 | 0 |

| **Independent Variable** | **Estimated Coefficient** | **Standard Error** | **t-Statistic** |
|---|---|---|---|
| Transfer Dummy | -2.39 | 0.081 | -29.48 |
| Walking time savings | 0.0042 | 0.00017 | 24.90 |

| auxiliary statistics | at convergence | initial |
|---|---|---|
| log likelihood | -1502.7 | -2179.9 |
| number of observations | 3145 | |
| percent correctly predicted | 77.997 | |

$\rho^2$ = 0.31066 Adjusted $\rho^2$ = 0.30974

This model confirms that there is indeed a trade off between making a transfer and walking time savings. Both coefficients show the expected sign and are highly significant. The coefficient of the dummy variable is negative, which means that, all else being equal, travelers will tend to avoid transfers in the subway system. The positive sign of walking time savings confirms that the more walking time saved by the transfer path, the more likely that riders will choose the transfer path. In this model, one transfer is equivalent to 2.39/ (0.0042 *60 ) = 9.52 minutes of walking time. This is the base estimate of the total transfer penalty that will be used in the later part of the thesis.

In discrete choice models, the adjusted $\rho^2$ serves as an informal goodness-of-fit index that measures the fraction of the initial log likelihood value explained by the model. Usually a value between 0.3 to 0.4 is a good result for the model specification, which is equivalent to an adjusted $R^2$ 0.7 to 0.85 for a linear regression model (Chu 2002). We expect that the adjusted $\rho^2$ will increase for more refined models.

### 4.2 System Model B

A series of models will be presented to describe the effects of the transit system on the transfer penalty. First, I will test how the layout of the transit system affects the transfer penalty. Then, station attributes are added to test how the penalty is affected by transfer stations.

#### 4.2.1 System Network Model B-1

This model recognizes that there will typically be an in-vehicle time difference as well as a walking time difference between the transfer and non-transfer paths, and variable represents the contribution of the transit network to the transfer penalty.

Model B-1

| | $\beta_1$ | $\beta_2$ | $\beta_3$ |
|---|---|---|---|
| Transfer Option Utility | 1 | Walking Time Savings | Extra In-Vehicle Time |
| Non-transfer Option Utility | 0 | 0 | 0 |

| Independent Variable | Estimated Coefficient | Standard Error | t- Statistic |
|---|---|---|---|
| Transfer Dummy | -2.30 | 0.084 | -27.26 |
| Walking time Savings | 0.0053 | 0.00021 | 25.32 |
| **Extra In-vehicle Time** | **-0.0036** | **0.00035** | **-10.205** |

| auxiliary statistics | at convergence | initial |
|---|---|---|
| log likelihood | -1434.4 | -2176.5 |
| number of observations | 3140 | |
| percent correctly predicted | 80.701 | |

$\rho^2$ = 0.34095 Adjusted $\rho^2$ = 0.33957

New variables are in bold font

Model B-1 has an improved goodness of fit compared to model A. The coefficient of extra in-vehicle time has a negative sign, indicating that additional in-vehicle time required for the transfer path reduces the likelihood that the transfer path is selected. Note that a one minute change in walking time is worth more than a similar change in in-vehicle time. The typical passenger perceives 1 minute of walking time savings to be equivalent to 1.47 minutes of in-vehicle time. One transfer in this model is equivalent to 2.30 / (0.0053 * 60 ) = 7.28 minutes of walking time savings. This is lower than model A since the effect of extra in-vehicle time was contributing to the unattractiveness of the transfer option. We assume that the remaining penalty is caused by attributes of transfer stations. The reduction of the transfer penalty, 2.24 minutes of walking time savings, is contributed by the layout of the transit network. This suggests that for the MBTA subway system, the network contributes a quarter of the total transfer penalty.

### 4.2.2 Facility Effect Models

We now add the four transfer station attributes to model B-1 to capture their effects on the transfer penalty. First, transfer walking time and transfer waiting time are added. This model is developed specifically for comparison with the 1997 CTPS study, because it does not have the other two variables.

The result for Model B-2 shows a substantial increase in goodness of fit although the transfer waiting time is only marginally significant, which means it has a less important role in determining people choice to transfer compared with the other time variables. This is a reasonable result considering that there is no great variation of waiting times among MBTA subway lines. In this model, one transfer is equivalent to 6.58 minutes of waiting time. This model provides a transfer penalty estimate in addition to transfer waiting time, transfer walking time, and

Model B-2

| | $\beta_1$ | $\beta_2$ | $\beta_6$ | $\beta_4$ | $\beta_5$ |
|---|---|---|---|---|---|
| Transfer Option Utility | 1 | Walking Time Savings | Extra In-vehicle Time | Transfer Walking Time | Transfer Wait Time |
| Non-transfer Option Utility | 0 | 0 | 0 | 0 | 0 |

| **Independent Variable** | **Estimated Coefficient** | **Standard Error** | **t- Statistic** |
|---|---|---|---|
| Transfer dummy | -0.98 | 0.20 | -4.84 |
| Walking time savings | 0.0047 | 0.0002 | 21.69 |
| Extra In-vehicle time | -0.0031 | 0.00042 | -7.31 |
| **Transfer walking time** | **-0.018** | **0.0015** | **-12.46** |
| **Transfer waiting time** | **-0.0025** | **0.0015** | **-1.67** |

| auxiliary statistics | at convergence | initial |
|---|---|---|
| log likelihood | -1335.1 | -2176.5 |
| number of observations | 3140 | |
| percent correctly predicted | 81.688 | |

$\rho^2$ = 0.38560 Adjusted $\rho^2$ = 0.38330

extra in-vehicle time. This is a relatively low value compared to the findings from the CTPS study as shown in Table 4-1.

Table 4-1 A Comparison between CTPS Report and This Research

| | CTPS, 1997 | Model B-2 |
|---|---|---|
| Variables in the Utility Function | Transfer dummy<br>In-vehicle time<br>Walking time<br>Waiting time<br>Transfer waiting time<br>Out-of-vehicle time<br>Transit fare | Transfer Dummy<br>In-vehicle time<br>Walking time<br>Waiting time<br>Transfer time |
| System and Choice | Auto and Transit, Path and Modal Choice | Subway, Partial Path Choice |
| Value of the Transfer Penalty | 12 to 15 in-vehicle minutes | 5.25 in-vehicle minutes |

The smaller transfer penalty may be due to 1) in our data set the transfer takes place in the subway system, which has a better transfer environment than many other locations; 2) the subway system in Downtown Boston has been well developed with a dense network, which make transfers relatively easy; 3) we only capture the trade off of transfer and travel times during the final stage of a trip and only for current transit riders.

Another way of interpreting these results is that this penalty exists over and above the disutility associated with transfer waiting time. The average waiting time is about 2 minutes in Downtown Boston subway stations. So the transfer penalty is about 3.5 times the transfer waiting time disutility . Using one headway as the transfer penalty will in this case underestimate the disutility of transfers.

In the next model, I will add the other two transfer station variables to model B-2. So this model includes all the defined subway system variables. If there is still a transfer penalty captured by the transfer dummy, we define it as the pure penalty, which reflects other attributes of the transfer.

Model B-3

| | $\beta_1$ | $\beta_2$ | $\beta_5$ | $\beta_6$ | $\beta_7$ | $\beta_8$ | $\beta_9$ |
|---|---|---|---|---|---|---|---|
| Transfer Option Utility | 1 | Walking Time Savings | Transfer Time | Wait | Level | Extra In-Vehicle Time | Concession |
| Non-transfer Option Utility | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| Independent Variable | Estimated Coefficient | Standard Error | t- Statistic |
|---|---|---|---|
| Transfer dummy | -0.597 | 0.268 | -2.23 |
| Walking time savings | 0.0046 | 0.00012 | 20.86 |
| Extra In-vehicle time | -0.0031 | 0.00043 | -7.17 |
| Transfer walking time | -0.019 | 0.0016 | -12.20 |
| Transfer waiting time | -0.00314 | 0.0016 | -1.96 |
| **Change of level** | **-0.25** | **0.135** | **-1.88** |
| **Concession** | **-0.156** | **0.123** | **-1.27** |

| auxiliary statistics | at convergence | initial |
|---|---|---|
| log likelihood | -1334.3 | -2176.5 |
| number of observations | 3140 | |
| percent correctly predicted | 81.592 | |
| $\rho^2 = 0.38696$ | Adjusted $\rho^2 = 0.38374$ | |

In this model, the change of level variable is marginally significant, while the concession variable is not significant, and the adjusted $\rho^2$ remains the same as in model B-2. Therefore, this model does not have better explanatory power than model B-2. However, the transfer penalty captured by the transfer dummy decreases significantly. One transfer is equivalent to 0.597 / (0.0046 *60) = 2.16 minutes of walking time savings. The ratio of the pure penalty to the total penalty is 2.16/ 9.52 = 22.7 %. We can say that the general condition of transfer stations contributes about a quarter of the total transfer penalty in the MBTA subway system.

If the transfer involves a change of level, the change is equivalent to 13 seconds in addition to the time spent on the stairs.

**4.3 Station Variation Models C**

The transfer penalty is likely to vary depending on the transfer facility itself. This model captures the transfer penalty in the four major transfer stations in Downtown Boston: Park Street, Government Center, Downtown Crossing, and State. Three station dummy variables are added to the model and Park Street is used as the base for comparison.

### 4.3.1 General Variation Model

We will first add the dummies to model B-1 without any specific transfer station attributes, so that the dummies capture the general variation of the transfer penalty across transfer stations.

Model C-1

| | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | $\beta_5$ | $\beta_6$ |
|---|---|---|---|---|---|---|
| Transfer Option Utility | 1 | Walking Time savings | Extra In-Vehicle Time | GOVT | STAT | DTXG |
| Non-transfer Option Utility | 0 | 0 | 0 | 0 | 0 | 0 |

| Independent Variable | Estimated Coefficient | Standard Error | t- Statistic |
|---|---|---|---|
| Transfer dummy | -1.39 | 0.11 | -12.62 |
| Walking time savings | 0.0048 | 0.00021 | 23.026 |
| Extra In-vehicle Time | -0.0034 | 0.00037 | -9.29 |
| **GOVT** | **-1.21** | **0.17** | **-7.15** |
| **STAT** | **-1.41** | **0.196** | **-7.21** |
| **DTXG** | **-1.09** | **0.106** | **-10.25** |

| auxiliary statistics | at convergence | initial |
|---|---|---|
| log likelihood | -1368.2 | -2176.5 |
| number of observations | 3140 | |
| percent correctly predicted | 81.943 | |

$\rho^2 = 0.37138$ Adjusted $\rho^2 = 0.36862$

All dummy coefficients are highly significant and have a negative sign. Therefore, Park Street is different from the other three transfer stations in terms of the transfer penalty. The negative signs of the three dummy variables indicate that passengers prefer transferring at Park Street rather than at Government Center, Downtown Crossing, or State. This is a reasonable result considering the convenient connections between Red Line and Green Line at Park Street Station.

To test if the three stations themselves are different from each other in terms of the transfer penalty, I made the following tests. To compare Government Center and State, a statistic is calculated as the follows. Var $(\beta_4 - \beta_5)$ = var $(\beta_4)$ + var $(\beta_5)$ – 2 Cov $(\beta_4 - \beta_5)$ = 0.0288 + 0.0384 – 2* 0.0613 = 0.1982 . Here, $\beta_4$ is the coefficient of Government Center, $\beta_5$ is the coefficient of State, and $\beta_6$ is the coefficient of Downtown Crossing. The test statistic for the null hypothesis $\beta_4 = \beta_5$ is given by $(\beta_4 - \beta_5)$/ SQRT Var $(\beta_4 - \beta_5)$ = 0.198/0.234 = 0.847 . So we can not reject the null hypothesis. The test statistic for the null hypothesis $\beta_4 = \beta_6$ is given by $(\beta_4 - \beta_6)$/ SQRT Var $(\beta_4 - \beta_6)$ = 0.126/0.166 = 0.759. So we can not reject the null hypothesis. The test statistic for the null hypothesis $\beta_5 = \beta_6$ is given by $(\beta_5 - \beta_6)$/ SQRT Var $(\beta_5 - \beta_6)$ = 0.325/0.192 = 1.69 . In this case we can reject the null hypothesis at the 0.1 level but not at a 0.05 level.

The analysis indicates that State and Downtown Crossing might be statistically different from each other in terms of the transfer penalty, but there is statistically no difference between Government Center and State, or between Government Center and Downtown Crossing. It seems reasonable that Park Street is different and the other stations, by comparison, are similar to each other in their transfer attractiveness.

Now the transfer dummy captures the common part of the transfer penalty after the variation across stations is accounted for by the station dummies. As expected, the coefficient of the transfer dummy decreases from Model B-2, and one transfer is now equivalent to $-1.39 / (0.00482 * 60) = 4.80$ minutes of walking time savings, about half of the originally estimated total penalty. The coefficients of the three station dummies show how much the extra transfer penalty is in the three stations in addition to the common part of the transfer penalty. This suggests that the transfer penalty at Park is about half of that at State, Government Center, or Downtown Crossing. The explanatory power of this model is better that Model B-1 but not as good as Model B-3

### 4.3.2 Specific Variation Model

Next, I add transfer walking time, transfer waiting time, change of level, and concession variables to see how these common factors affect the explanatory power of the whole model as well as the size and significance of the transfer station dummies.

Model C-2 has improved explanatory power and new variables are strongly significant and have the expected signs. The more transfer walking time and transfer waiting time the less likely people are to transfer. Transfer walking time is much more onerous than transfer waiting time. For the typical passenger, 1 minute of transfer walking time is perceived as being equivalent to 6.79 minutes of transfer waiting time, 5.27 minutes of walking time savings, and 6.45 minutes of in-vehicle time. This indicates that reducing the transfer walking time between subway lines has the most significant impact on the transfer penalty.

Note change of level and concession dummies become highly significant with the transfer station dummies included. The negative sign of the change of level dummy indicates that if there is a change of level between two subway lines, people are less likely to transfer. The positive sign of the concession dummy shows that the existence of a concession on the transfer platform promotes transfer activities.

The negative sign of the GOVT dummy means that after capturing the effects of transfer time, waiting time, level of change, and concessions, Government Center is still reviewed as a less convenient transfer station than Park Street. On the contrary, the DTXG dummy shows a positive sign, which means, Park Street is perceived to be a better transfer station than Downtown Crossing when accounting for the differences in specific station attributes.

Model C-2

| | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | $\beta_5$ | $\beta_6$ | $\beta_7$ | $\beta_8$ | $\beta_9$ | $\beta_9$ |
|---|---|---|---|---|---|---|---|---|---|---|
| Transfer Option Utility | 1 | Walking Time savings | GOVT | STAT | DTXG | Transfer Time | Wait | Vertical | Extra In-Vehicle Time | Concession |
| Non-transfer Option Utility | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Independent Variable** | **Estimated Coefficient** | **Standard Error** | **t- Statistic** |
|---|---|---|---|
| Transfer dummy | -0.27 | 0.27 | -0.999 |
| Walking Time savings | 0.0049 | 0.00024 | 20.63 |
| Extra In-vehicle Time | -0.004 | 0.00048 | -8.33 |
| GOVT | -2.23 | 0.23 | -9.70 |
| STAT | -0.092 | 0.27 | -0.34 |
| DTXG | 0.48 | 0.21 | 2.29 |
| **Transfer walking time** | **-0.0258** | **0.0028** | **-9.13** |
| **Transfer waiting time** | **-0.0038** | **0.0017** | **-2.22** |
| **Level** | **-0.52** | **0.15** | **-3.36** |
| **Concession** | **1.05** | **0.17** | **6.05** |

| auxiliary statistics | at convergence | initial |
|---|---|---|
| log likelihood | -1278.2 | -2176.5 |
| number of observations | 3140 | |
| percent correctly predicted | 82.484 | |
| $\rho^2$ = 0.41270 | Adjusted $\rho^2$ = 0.4081 | |

This means that Downtown Crossing is perceived to be better than Park Street on other non-observed dimensions.

Note that the transfer dummy and the STAT dummy are no longer significant. This implies that the four variables capture the entire common transfer penalty across the transfer stations as well as the variation of the transfer penalty between State and Park Street. The transfer penalty disappears in this model. Dropping these two variables gives model C-3, which is the best model specification so far. Note as expected the coefficients of all variables remain almost the same as model C-2.

Model C-3

| | $\beta_1$ | $\beta_2$ | $\beta_3$ | $\beta_4$ | $\beta_5$ | $\beta_6$ | $\beta_7$ | $\beta_8$ |
|---|---|---|---|---|---|---|---|---|
| Transfer Option Utility | Walking Time savings | GOVT | DTXG | Transf er Time | Wait | Extra In-Vehicle Time | Vertical | Conces sion |
| Non-transfer Option Utility | 0 | 0 | 0 | 0 | 0 | 0 | 0 | 0 |

| **Independent Variable** | **Estimated Coefficient** | **Standard Error** | **t- Statistic** |
|---|---|---|---|
| Transfer time | -0.027 | 0.0022 | -12.34 |
| Waiting time | -0.0053 | 0.0011 | -4.82 |
| Walking Time Savings | 0.0049 | 0.00023 | 21.35 |
| Extra In-vehicle Time | -0.004 | 0.00048 | -8.34 |
| GOVT | -2.26 | 0.23 | -9.90 |
| DTXG | 0.53 | 0.15 | 3.45 |
| Level | -0.59 | 0.11 | -5.39 |
| Concession | 1.06 | 0.17 | 6.19 |

| auxiliary statistics | at convergence | initial |
|---|---|---|
| log likelihood | -1278.9 | -2176.5 |
| number of observations | 3140 | |
| percent correctly predicted | 82.611 | |
| $\rho^2$ = 0.41240 | Adjusted $\rho^2$ = 0.40872 | |

The following table lists the change of the penalty with variables added step by step in each version of the model so far.

Table 4-2 A Summary of Models in A-C

| Model Number | Variables in the Utility Function | Name of the Penalty | Adjusted $\rho^2$ | Equivalent Value of the Penalty |
|---|---|---|---|---|
| A | Transfer Dummy<br>Walking Time | The Total Penalty | 0.309 | 9.52 walking minutes |
| B-1 | Transfer Dummy<br>Walking Time<br>**In-vehicle Time** | | 0.338 | 7.28 walking minutes |
| B-2 | Transfer Dummy<br>Walking Time<br>In-vehicle Time<br>**Transfer Time**<br>**Waiting Time** | | 0.383 | 3.14 walking minutes |
| B-3 | Transfer Dummy<br>Walking Time<br>In-vehicle Time<br>Transfer Time<br>Waiting Time<br>**Level of Change**<br>**Concession** | The Pure Penalty | 0.383 | 2.16 walking minutes |
| C-1 | Transfer Dummy<br>Walking Time<br>In-vehicle Time<br>**Station Dummies** | The Least Penalty across all transfer stations | 0.368 | 4.80 walking minutes |
| C-3 | Transfer Dummy<br>Walking Time<br>In-vehicle Time<br>Transfer Time<br>Waiting Time<br>Level of Change<br>Concession<br>**Station Dummies** | The transfer penalty disappears | 0.408 | 0.0 walking minutes |
| All new variables are in bold font | | | | |

## 4.4 Environmental Model D

In this section, variables outside the subway system are added to test their effects on the transfer penalty. There are four types of variables in this section: land use, road network, topology, and open space. In this model, we are not only concerned with the difference of environment between non-transfer and transfer paths but with how the environment along the alternative paths affects the transfer penalty. For each of the four factors, there are at least two variables: one captures the difference between the two paths, and the other captures the non-transfer path effects.

The adjusted $\rho^2$ increases significantly compared with model C-3. All environmental variables have the expected signs, but some of them are not significant. Specifically, there are three variables included to capture the effects of Beacon Hill, but two of them are not significant, which means that Beacon Hill affects the transfer choice only when the non-transfer path runs through this area while the transfer path does not. Deleting the two variables and the transfer waiting time variable, which is also insignificant, I get model D-2.

Model D-1

| | $\beta_1$ | $\beta_{2-9}$ | $\beta_{10}$ | $\beta_{11}$ | $\beta_{12}$ | $\beta_{13}$ | $\beta_{14}$ | $\beta_{15}$ | $\beta_{16}$ | $\beta_{17}$ | $\beta_{18}$ |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Transfer Option Utility | 1 | Model C-3 Variables | 0 | DIF_PFP | 0 | DIF_W_TP | 0 | T_HILL | BOTH_HILL | 0 | BOTH_COM |
| Non-transfer Option Utility | 0 | | W_PFP | 0 | W_SW | 0 | W_HILL | 0 | 0 | W_COM | 0 |

| Independent Variable | Estimated Coefficient | Standard Error | t- Statistic |
|---|---|---|---|
| Transfer dummy | -1.43339 | 0.42 | -3.40 |
| transfer walking time | -0.024 | 0.0024 | -10.07 |
| transfer waiting time | -0.002 | 0.0019 | -1.033 |
| Walking Time Savings | 0.005 | 0.00026 | 19.11 |
| Extra In-vehicle Time | -0.0046 | 0.0005 | -9.1 |
| GOVT | -2.60 | 0.26 | -9.98 |
| DTXG | 0.50 | 0.17 | 2.93 |
| Level | -0.50 | 0.15 | -3.33 |
| Concession | 1.53 | 0.21 | 7.27 |
| **Non-transfer PFP density** | **-0.32** | **0.15** | **-2.14** |
| **Extra PFP density** | **-0.29** | **0.07** | **-4.05** |
| **Non-transfer sidewalk width** | **-0.028** | **0.01** | **-2.41** |
| **Extra sidewalk width** | **-0.017** | **0.0093** | **-1.84** |
| **Only non-transfer Hilly** | **1.33** | **0.38** | **3.50** |
| **Only transfer Hilly** | **0.456** | **0.84** | **0.54** |
| **Both Hilly** | **-0.516** | **0.52** | **-0.98** |
| **Only non-transfer common** | **-1.64** | **0.36** | **-4.52** |
| **Both Common** | **-0.73** | **0.39** | **-1.89** |

| auxiliary statistics | at convergence | initial |
|---|---|---|
| log likelihood | -1217.8 | -2176.5 |
| number of observations | 3140 | |
| percent correctly predicted | 82.834 | |

$\rho^2 = 0.44047$ adjusted $\rho^2 = 0.43220$

Note the adjusted $\rho^2$ does not change, but the percent of correctly predicted increases slightly. This is the best model specification so far. For the land use factor, both the difference of PFP density and the PFP density along the non-transfer path are significant with negative signs. However, the coefficient of the second variable is bigger than that of the first one in absolute value ( 0.32 vs 0.28) indicating that the PFP density along the non-transfer path is more important than the difference of PFP density between the transfer and non-transfer paths. The sidewalk variables show a similar pattern although the difference of average sidewalk width between non-transfer and transfer path is only marginally significant. For the open space factor, when both paths run through Boston Common, passengers are still less likely to transfer. All these facts suggest that 1) if the non-transfer path provides a better pedestrian environment than the transfer path, people are less likely to transfer; and 2) more interesting even there is no environmental difference between the two paths, if the pedestrian environment in general is good, people are willing to leave the subway system early rather than choose to transfer.

In this model the transfer dummy is again significant, and one transfer is equivalent to 5.78 minutes of walking time savings. An explanation is that Downtown Boston provides a good pedestrian environment, which increases the transfer penalty, and when riders choose to stay longer in the subway system they lose the opportunity to walk out and enjoy the outside urban amenities.

Model D-2

| | $\beta_1$ | $\beta_{2-8}$ | $\beta_9$ | $\beta_{10}$ | $\beta_{11}$ | $\beta_{12}$ | $\beta_{13}$ | $\beta_{14}$ | $\beta_{15}$ |
|---|---|---|---|---|---|---|---|---|---|
| Transfer Option Utility | 1 | Model C-3 Variables | 0 | DIF_PFP | 0 | DIF_W_TP | 0 | 0 | BOTH_COM |
| Non-transfer Option Utility | 0 | | W_PFP | 0 | W_SW | 0 | W_HILL | W_COM | 0 |

| Independent Variable | Estimated Coefficient | Standard Error | t- Statistic |
|---|---|---|---|
| Transfer dummy | -1.77 | 0.28 | -6.29 |
| transfer walking time | -0.024 | 0.0024 | -10.02 |
| Walking Time Savings | 0.0051 | 0.00026 | 19.58 |
| Extra In-vehicle Time | -0.0047 | 0.00049 | -9.60 |
| GOVT | -2.57 | 0.26 | -9.95 |
| DTXG | 0.49 | 0.167 | 2.97 |
| Level | -0.44 | 0.14 | -3.12 |
| Concession | 1.48 | 0.20 | 7.25 |
| Non-transfer PFP density | -0.32 | 0.15 | -2.10 |
| Extra PFP density | -0.28 | 0.07 | -3.95 |
| Non-transfer sidewalk width | -0.03 | 0.011 | -2.78 |
| Extra sidewalk width | -0.0145 | 0.0089 | -1.64 |
| Only non-transfer Hill | 1.39 | 0.346 | 4.03 |
| Only non-transfer common | -1.68 | 0.33 | -5.04 |
| Both Common | -0.74 | 0.36 | -2.05 |

| auxiliary statistics | at convergence | initial |
|---|---|---|
| log likelihood | -1219 | -2176.5 |
| number of observations | 3140 | |
| percent correctly predicted | 83.057 | |

$\rho^2 = 0.43991$ adjusted $\rho^2 = 0.43302$

There are other interesting findings. If Beacon Hill is only on the non-transfer path, people are willing to walk 1.39/(0.0051*60)= 4.54 minutes further to avoid Beacon Hill. If Boston Common is only on the non-transfer path, people are willing to walk 1.68/ (0.0051*60) = 5.49 minutes further.

### 4.5 Trip and Demographic Model E

It is believed that the trip and demographic characteristics might also affect the transfer penalty. There are four attributes in the trip characteristic category, and eight attributes in the demographic category. ( see the Appendix for the survey questionnaire). Table 4-4 lists all 12 attributes and the variables associated with them. All are included as dummy variables.

After a number of tests and adjustments, a final model is present with only four trip and demographic variables. Three of them are marginally significant, but deleting them will reduce the explanatory power of the model. The extra sidewalk width variable is also excluded, but a statistical test shows this does not affect the model. So model E-1 is the best and also the final model specification of this research.

Table 4-3 Trip and Demographic Factors

| Category | Factors | Variables |
|---|---|---|
| Trip Characteristics | Boarding Time | Boarding from 11:45am to 3:00pm<br>Boarding from 6:30am to 8:45am |
| | Fare Type | Token or cash |
| | Trip Purpose | Work<br>Home<br>School<br>Doctor or personal business<br>Recreation |
| | Frequency | Use the subway < 3 days per week<br>Use the subway >= 5 days per week<br>Oneway trip<br>The first trip of a round trip |
| Demographic Characteristics | Gender | Female |
| | Age | Youth under 18 years old<br>Aging over 65 years old |
| | Income | Low household income < $30,000<br>High household income > $60,000 |
| | Occupation | Student<br>Retired<br>Unemployment |
| | Household Size | Only one member in the household<br>>= 3 members in the household |
| | License | With driver license or not |
| | Auto Availability | Auto availability when making the trip |
| | Car Ownership | Own <= 1 car |

Model E

| | $\beta_1$ | $\beta_{2\text{-}15}$ | $\beta_9$ | $\beta_{10}$ | $\beta_{11}$ |
|---|---|---|---|---|---|
| | | | SCHOOL | HIGH | FEW_CAR |
| Transfer Option Utility | 1 | Model D-2 Variables without DIF_SW | | | |
| Non-transfer Option Utility | 0 | | 0 | 0 | 0 |

| Independent Variable | Estimated Coefficient | Standard Error | t- Statistic |
|---|---|---|---|
| Transfer dummy | -1.83 | 0.30 | -6.12 |
| transfer walking time | -0.023 | 0.0024 | -9.91 |
| Walking Time Savings | 0.0051 | 0.00026 | 19.62 |
| Extra In-vehicle Time | -0.0047 | 0.00049 | -9.59 |
| GOVT | -2.59 | 0.26 | -9.99 |
| DTXG | 0.53 | 0.17 | 3.14 |
| Level | -0.45 | 0.14 | -3.19 |
| Concession | 1.53 | 0.20 | 7.42 |
| Non-transfer PFP density | -0.29 | 0.15 | -1.94 |
| Extra PFP density | -0.28 | 0.071 | -3.96 |
| Non-transfer sidewalk width | -0.031 | 0.011 | -2.87 |
| Extra Sidewalk width | -0.012 | 0.0089 | -1.33 |
| Only non-transfer Hill | 1.40 | 0.35 | 4.05 |
| Only non-transfer common | -1.68 | 0.33 | -5.02 |
| Both Common | -0.70 | 0.36 | -1.92 |
| **School** | **-0.74** | **0.40** | **-1.84** |
| **Round trip** | **-0.17** | **0.11** | **-1.53** |
| **>= 3 household members** | **0.21** | **0.11** | **1.93** |
| **Own <= 1 car** | **0.40** | **0.14** | **2.85** |

| auxiliary statistics | at convergence | initial |
|---|---|---|
| log likelihood | -1210.8 | -2176.5 |
| number of observations | 3140 | |
| percent correctly predicted | 83.248 | |

$\rho^2 = 0.44371$ adjusted $\rho^2 = 0.43498$

Only the car ownership variable is strongly significant. A possible explanation is that if people own few cars, they tend to use the subway frequently, and are thus more familiar with the subway system. This can reduce the transfer penalty. However, the frequency variables defined as the number of days that the rider use the subway system is not significant, which contradicts to this explanation. The other three variables are marginally significant. The transfer penalty captured by the transfer dummy does not change much. All indications are that the trip and demographic characteristics do not significantly affect the transfer penalty. This is an acceptable result because we only include riders who already have chosen to use the subway system in this analysis. Difference among these people is less than that among the whole population.

# Chapter 5 Conclusions

Transfer activities are critical to the daily operation of a transit system. However, people do not like to transfer, and the reluctance of passengers to transfer can be thought of as a "penalty". The term transfer penalty describes passenger's transfer perception for a transit system, and a clear understanding of the penalty can enhance ridership forecasting, network design, station design, service design, service management, and the marketing strategy of a transit system. Because it is subjective and based on people's perceptions, it is difficult to measure and analyze the transfer penalty. In practice, some transit systems make simple assumptions about the transfer penalty in a subjective way. Research on the transfer penalty has used different methods, dealt with different parts of the transfer penalty, and thus ended up with different results. This research adopts a new method to measure the transfer penalty based on a standard on-board survey data set, and the use of GIS and spatial analysis method to identify and computer the actual trips with alternative paths that did (not) involve a transfer. A series of binary choice models are developed with the assistance of GIS techniques. The effects of different system and environmental factors on the transfer penalty are captured and analyzed in detail. The method is believed to be more accurate and comprehensive than previous methods, though it also has limitations. This chapter draws conclusions on this method, the data process procedure, the model development, and final results.

## 5.1 The method

Because the transfer penalty is a subjective perception, it is hard to measure directly. However, because people usually make the transfer decision after they weigh the "penalty" and the benefit of the transfer, we can assess the penalty if we can measure the transfer benefit. There are many different transfer types, and thus different types of benefit. For example, for a transfer between car and subway, the benefit might be the total travel time saved and any difference in cost from the origin to the destination. This research focuses on transfers between subway lines at the end of transit trips. In this case, one of the benefits of transferring could be the saved walking time from the egress station to the destination.

Compared to previous methods, the advantage of this method is that the benefit is clearly defined. The "best" alternative to the chosen path is clearly identified and the trade off between one transfer and the walking time saved is easily understandable especially when there are no competing modes to a subway system except walking. The on board survey provides detailed information on how a transfer is performed. The limitation of this method is that it targets a particular population: people who already choose transit, and a particular type of trips: trips which end in the study area. People who do not choose the transit, and trips that end in other areas even though they involve transfers are excluded. So we must be cautious when applying the results of this research to other populations and trips.

Downtown Boston is selected as the study area, and the MBTA subway system is the targeted transit system. So the transfer penalty analyzed reflects the situation of this system, but the method can be easily applied to other transit systems as far as standard on board survey data are available.

### 5.2 Data Processing

The major task of data processing is to define the transfer and non-transfer path in and outside the transit system, define factors that might affect the transfer penalty, and calculate these factors for both paths.

First, I select trips that end within Downtown Boston with both transfer and non-transfer options. Note that not all trips have both options. If the destination is very near to the boarding subway line, people will go to the destination directly, and not think about transferring. So both options exist when the destination is closer to another line. To define the travel path of each option, I find the nearest station on the boarding line and on the "another" line. The path within the system from the origin to the two stations can be easily defined. The path from the two stations to the destination can be found by using GIS to computer the shortest path through the street network.

Second, four groups of factors that might affect the transfer penalty are defined. The station factors describe how specific transfer station attributes affect the penalty. The path factors capture the influence of the transit network on the penalty. Environmental factors describe the environmental influence on the penalty. Trip and demographic factors capture the variation of the penalty across trips and passengers. Note some factors may belong to two groups. All these factors are calculated for both transfer and non-transfer paths, and will enter into the model.

### 5.3 Model Development

Model specification starts with a simple model that aggregates all the transfer penalty effects into one transfer dummy, which is the total transfer penalty measured in terms of the minutes of walking time savings. Then new variables are added to the model, and their impacts on the transfer penalty are estimated. First, station and path factors are added to capture the influence of the transit system on the transfer penalty. Second, three transfer station dummies are added to capture the variation of the penalty across transfer stations. A combination of station characteristics and station dummies can account for all of the transfer penalty in the simple model. Next, environmental, trip, and demographic factors are added to test their influence on the transfer penalty. The results are interesting but complex, and summarized below after reviewing the models. There are a total of 10 models presented in this research.

Table 5-1 Change of the Transfer Penalty and the Goodness of Fit of Models II

| Model Number | Variables in the Utility Function | Name of the Penalty | Adjusted $\rho^2$ | Equivalent Value of the Penalty |
|---|---|---|---|---|
| A | Transfer Dummy<br>Walking Time | The Total Penalty | 0.309 | 9.52 walking minutes |
| B-1 | Transfer Dummy<br>Walking Time<br>**In-vehicle Time** | | 0.338 | 7.28 walking minutes |
| B-2 | Transfer Dummy<br>Walking Time<br>In-vehicle Time<br>**Transfer Time**<br>**Waiting Time** | | 0.383 | 3.14 walking minutes |
| B-3 | Transfer Dummy<br>Walking Time<br>In-vehicle Time<br>Transfer Time<br>Waiting Time<br>**Level of Change**<br>**Concession** | The Pure Penalty | 0.383 | 2.16 walking minutes |
| C-1 | Transfer Dummy<br>Walking Time<br>In-vehicle Time<br>**Station Dummies** | The Least Penalty across all transfer stations | 0.368 | 4.80 walking minutes |
| C-3 | Transfer Dummy<br>Walking Time<br>In-vehicle Time<br>Transfer Time<br>Waiting Time<br>Level of Change<br>Concession<br>**Station Dummies** | The transfer penalty disappears | 0.408 | 0.0 walking minutes |
| D-2 | Transfer Dummy<br>Walking Time<br>In-vehicle Time<br>Transfer Time<br>Waiting Time<br>Level of Change<br>Concession<br>Station Dummies<br>**Environmental Variables** | Environmental effects on the transfer penalty | 0.433 | 5.78 walking minutes |
| All new variables are in bold font | | | | |

### 5.4 Summary of Research Findings

#### 5.4.1 The Total Penalty

The total transfer penalty is equivalent to 9.52 minutes of walking time (Model A). This means that in Boston MBTA subway system, people are generally willing to transfer if one transfer saves more than 9.52 minutes of walking time. This equals 760 meters, or 0.47 miles, of walking distance, which is consistent with my previous finding from the data that one transfer saves 722 meters, or 0.45 miles, of walking distance (see page 48). The transfer penalty is relatively low compared to previous studies. This is because 1) the transfer happens in a subway system, which has a better transfer environment compared to other systems; 2) the subway system in Boston Downtown has been well developed with a dense network, which makes transfers easy to perform; 3) we only capture the trade off of transfer and travel times during the final stage of a trip and only for current transit riders.

#### 5.4.2 Factors Within the System

With more factors entering into the model, the transfer penalty captured by the transfer dummy decreases, while the goodness of fit of the model increases. (See Table 5-1)

Each of the factors account for part of the transfer penalty. The network influence of the subway system (Model B-1) accounts for 24% of the total transfer penalty. Another 53 % of the penalty is explained by station attributes including transfer walking time, transfer waiting time, and transfer facilities (Model B-3). The remaining transfer penalty, which we called the pure transfer penalty, contributes 23% of the total penalty. The fact that ¾ of the transfer penalty can be explained in terms of the physical characteristics of the stations implies that station design has an important impact on transfer behavior.

There is great variation among transfer stations in terms of the transfer penalty. The transfer penalty at Park Street, the best transfer station in the system, is only about half of that of State, Government Center, or Downtown Crossing. After capturing the transfer walking time, transfer waiting time, change of level, and concession, the remaining station effects are reduced. Park Street and State become similar in terms of the transfer penalty. Downtown Crossing become more conducive to transfer compared with Park Street after controlling for station factors defined in this research.

When all system factors including the transfer station dummies are included in the model, the transfer penalty disappears. This result indicate that all the transfer penalty for Park (the base case), State (no difference), and Downtown Crossing (better than base case) are explained by system characteristics. There is still a transfer penalty not explained by the model for Government Center.

### 5.4.3 Factors outside the System

The outside environment is likely to affect the transfer penalty because it affects people's perceptions of walking, which is the alternative to transferring. There are four factors considered: land use, sidewalk width, topology, and open space. The transfer penalty appears again in the model after these factors are added. The goodness of fit increases with an adjusted $\rho^2$=0.435, which is very high for any discrete choice model. This suggests that if the non-transfer path provides a better pedestrian environment than the transfer path, people are less likely to transfer. More interesting even there is no environmental difference between the two paths, if the pedestrian environment is good in general, people are willing to leave the subway system early rather than choose to transfer. An improved outside environment seems increase the transfer penalty for the subway system. This is perhaps because passengers lose the opportunity to enjoy the urban amenities if they choose to transfer and thereby stay longer in the subway system in order to shorter their walk.

There are other interesting findings. If Beacon Hill is only on the non-transfer path, people are willing to walk 1.39/(0.0051*60)= 4.54 minutes further to avoid Beacon Hill. If Boston Common is only on the non-transfer path, people are willing to walk 1.68/ (0.0051*60) = 5.49 minutes further.

### 5.4.4 Trip and Demographic Influences

There is some evidence that different types of trips and different population groups have different transfer rates. However, this research does not find significant effects of trip and demographic characteristics on the transfer penalty. Specifically, major trip and demographic factors such as boarding time, trip purpose, income, gender, and age are not significant. Round trips, household with more than 3 members, school trips are marginally significant. The only significant variable is the low car ownership, but I do not find a satisfactory explanation for this. The transfer penalty captured by the transfer dummy remains almost the same, and the goodness of fit also does not change.

All these results suggest that the transfer penalty does not vary across trip and demographic characteristics. It is determined by the transportation system rather than by the user attributes. However, it should be noted that this conclusion only applies to people who have already chosen the subway. Most demographic effects are likely to be on mode choice and frequency of subway use, not on the path they choose.

## 5.5 Future Research Directions

Transfer activities affect many aspects of the performance of a transit system. The estimated transfer penalty might have various implications for improving the service quality. The results might also be helpful to refine ridership forecasting models.

We only measured the transfer penalty for a particular population and a particular type of trips. It might be interesting to apply the same method to other population groups and trips, such as people who choose bus and transfers between bus lines, and people who choose commuter rail and transfer between commuter rail and subway lines. This will give us a more comprehensive picture of how the different transit systems are connected with each other, and what factors affect their integration and coordination.

It is interesting to further the exploration of how outside environmental factors affect the connection between transit service lines and between different transit systems. This will provide insight into how land use and transportation network interact with each other, and how a passenger transportation system can be designed, and managed in an environmentally friendly way.

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## Appendix A: Summary and Definition of Variables

### Table A-1 Variable Statistics

| Variables | Mean | Std Dev | Minimum | Maximum |
|---|---|---|---|---|
| **Time Variables** | | | | |
| Transfer walking Time (seconds) | 57.54 | 52.83 | 1.00 | 217.00 |
| Transfer Waiting Time (seconds) | 116.84 | 33.32 | 88.50 | 270.00 |
| Walking Time Savings (seconds) | 275.90 | 390.63 | 1.28 | 2244.20 |
| Extra In-vehicle Time (seconds) | 143.71 | 186.17 | -371.00 | 964.00 |
| **Environmental Variables** | | | | |
| Average Width of Sidewalk along the Non-transfer Walking Path (feet) | 21.8 | 9.02 | 2.46 | 56.82 |
| Extra Average Width of Sidewalk along the Non-transfer Walking Path (feet) | 0.70 | 9.09 | -38.8 | 27.00 |
| PFP Density along the Non-transfer Walking Path | 0.49 | 0.43 | 0.00 | 2.59 |
| Extra PFP Density along the non-transfer walking path | -0.06 | 0.96 | -13.63 | 2.37 |

### Table A-2 Variable Definitions

| | |
|---|---|
| **Dependent Variable** | |
| CHOICE | Transfer or not transfer to get to the destination in Boston Downtown |
| **Station Variables** | |
| TRANTIME | Transfer time defined by the walking time between platforms |
| WAIT | Waiting time for the train to transfer defined by the half headway |
| LEVEL | Dummy variable; 1 if the transfer option involves a level of change, 0 otherwise |
| CONCESON | Dummy variable; 1 if there is concessions on the transfer platform, 0 otherwise |
| **Path Variable** | |
| EXTRAIV | The extra in-vehicle time spent on transfer defined by transfer option in-vehicle time minus non-transfer option in-vehicle time |
| SAVEWALK | The walking time savings defined by walking time of the non-transfer option minus walking time of the transfer option |
| **Pedestrian Environment Variables** | |

| | |
|---|---|
| W_PFP | The density of Pedestrian Friendly Parcels (PFP) along the non-transfer path calculated as the number of PFPs per 100 meters |
| DIF_PFP | The extra density of Pedestrian Friendly Parcels (PFP) along the transfer path defined PFP density of transfer path minus PFP density of non-transfer path |
| W_SW | The average sidewalk width along the non-transfer walking path |
| DIF_SW | The average sidewalk width along the transfer path minus that along the non-transfer path |
| W_TP | Topology dummy; 1 if the non-transfer path runs through the Beacon Hill area, 0 otherwise |
| DIF_W_TP | Topology dummy; 1 if the non-transfer path runs through the Beacon Hill area while the transfer path does not, 0 otherwise |
| W_COM | Boston Common dummy; 1 if the non-transfer path runs through the Common, 0 otherwise |
| DIF_WCOM | Boston Common dummy; 1 if the non-transfer path runs through the Common while the transfer path does not, 0 otherwise |
| **Trip and Demographic Variables** | |
| BOD_NOON | Boarding time dummy; 1 if the boarding time is between 11:45am to 3:00pm, 0 otherwise |
| SCHOOL | Dummy variable; 1 if the trip purpose is school, 0 otherwise |
| HOME | Dummy variable; 1 if the trip purpose is home, 0 otherwise |
| ROUND | Frequency dummy; 1 if the person will take another subway trip in addition to the current one, 0 otherwise |
| STUDENT | Occupation dummy; 1 if the person is student, 0 otherwise |
| RETIRED | Occupation dummy; 1 if the person is retired, 0 otherwise |
| FEMALE | Gender dummy; 1 if the person is female, 0 otherwise |
| HH_3 | Household size dummy; 1 if there are more than 3 (including 3) members in the household, 0 otherwise |
| HH_1 | Household size dummy; 1 if there is only one person in the household, 0 otherwise |
| HIGH | Income dummy; 1 if the household income is above $60,000 |
| FEW_CAR | Car ownership dummy; 1 if the person own one or no car, 0 otherwise |
| **Station Dummies** | |
| GOVT | Station dummy, 1 if the transfer option is at Government Center, 0 otherwise |
| STAT | Station dummy, 1 if the transfer option is at State, 0 otherwise |
| DTXG | Station dummy, 1 if the transfer option is at Downtown Crossing, 0 otherwise |

## Appendix B: The Transfer Penalty between Different Modes

A transfer involves either a change of modes (auto to bus, bus to subway etc), or simply a change of vehicle (bus to bus, subway train to subway train). The value of the transfer penalty is likely to be dependent on the modal or path combination defining the transfer. For example, a transfer between auto and transit is likely to be less convenient than a transfer within a transit system because it requires finding a parking space, walking across the parking area, purchasing a ticket, and waiting for the train.

Liu's study shows that transfer penalties vary depending on the type of transfer, and that auto-to-rail transfer penalty is three times the rail-to-rail transfer penalty (Liu 1997). In another report by Wardman, Hine and Stradling (2001), the transfer penalty is measured for different modes. One transfer is valued at 4.5 in-vehicle minutes for bus users, 8.3 in-vehicle minutes for car users, and 8 in-vehicle minutes for rail users.

Using survey data for commuter trips in Stockholm in 1968 and 1971, Alger et *al* (1975) emphasized the impacts on user behavior of comfort and convenience variables such as waiting time and the number of transfers. The results show significant variation of the transfer penalty among different transfer types. Bus-to-bus transfer had the highest transfer penalty, equivalent to $ 0.40 US dollar (1971 prices). Alger et *al* also found that the physical convenience level between rail station platforms and feeder bus stops has considerable impacts on the transfer penalty. In Stockholm, transfers between rail modes always take place in a sheltered location where passengers can transfer by walking across a platform or by using elevators. The value of transfer penalty between rail modes is less than a third of that between buses.

## Appendix C: Technical Documents

### C.1 Walking Path Calculation

The network distances from egress stations to destinations are calculated using the spatial analysis function of ArcView 3.x. Two data layers are created: one is the destination point layer with 1313 locations representing 6229 trips, and the other one is the station point layer with 21 subway stations in Downtown Boston. The result is a polyline layer with all 6269 x 21 = 131649 walking paths. Each destination point has two paths connected to two subway stations. One represents the walking path of the transfer option, and the other one represents the non-transfer option. The distance of the two paths will be used to calculate the walking time of both options, and enter the model.

Avenue Script (Edit from ESRI sample script)

Purpose:

To calculate the least cost path from multiple origins to multiple destinations one at a time. The script determines the path from each origin to each destination separately. A view with a line theme and two point themes (origins and destinations) are required.

```
aView = av.GetActiveDoc
if (not (aView.Is(View))) then
  msgBox.Error("Active document is not a view.","")
  exit
end

theLineThemes={}
for each t in aView.GetThemes
  if (NetDef.CanMakeFromTheme(t)) then
```

```
    theLineThemes.add(t)
  end
end
aNetTheme=msgbox.List(theLineThemes,"Select the Network theme",
                "Solve point to point along network")
if (aNetTheme = nil) then
  msgBox.Error("Network theme not found.","")
  exit
end
aNetDef = NetDef.Make(aNetTheme.GetFTab)
if (aNetDef.HasError) then
  msgBox.Error("NetDef has error.","")
  exit
end

'******************************
' make the Network object
'******************************

aNetwork = Network.Make(aNetDef)
theSearchTol=aNetwork.GetSearchTol.asstring
theNewTol=msgbox.input("Current search tolerance","Use a different search?",theSearchTol)
if(theNewTol<>NIL) then
  if(theNewTol.AsNumber.Is(Number)) then
    theNewTol=theNewTol.AsNumber
  else
    theNewTol=theSearchTol
  end
else
  exit
end
aNetwork.SetSearchTol(theNewTol)

'**************************************************
' get the origin and destination point themes
'**************************************************

thePointThemes={}
for each t in aView.GetThemes
  if (t.GetFTab.GetSrcName.GetSubName = "Point") then
    thePointThemes.add(t)
   end
end
theOriginTheme=msgbox.List(thePointThemes,"Select the origin theme",
                   "Solve point to point along network")
theDestTheme=msgbox.List(thePointThemes,"Select the destination theme",
                  "Solve point to point along network")

'*************************************
' check if a stop theme was found
'*************************************

if ((theOriginTheme = nil) or (theDestTheme=nil)) then
  msgBox.Error("Theme not found or selected.","")
  exit
end
```

```
theOriginFTab = theOriginTheme.GetFTab
theOriginShapeFld = theOriginFTab.FindField("Shape")
theOriginFlds=theOriginFTab.GetFields.Clone
theOriginFlds.Remove(0)
theOriginLabelFld=msgbox.List(theOriginFlds,"Select a label field",
                    "Origin theme")
theOWidth=theOriginLabelFld.GetWidth

theDestFTab =theDestTheme.GetFTab
theDestShapeFld = theDestFTab.FindField("Shape")
theDestFlds=theDestFtab.GetFields.Clone
theDestFlds.Remove(0)
theDestLabelFld=msgbox.List(theDestFlds,"Select a label field",
                    "Destination theme")
theDWidth=theDestLabelFld.GetWidth

theOutFName=FileDialog.Put((av.GetProject.GetWorkDir.asString+"\Paths.shp").AsFileName,
                   "*.shp","Specify a output filename and saving folder")
if(theOutFName=NIL) then
  exit
end
theOutFTab=FTab.MakeNew(theOutFName,Polyline)
theOutIDFld=Field.Make("ID",#FIELD_DECIMAL,6,0)
theOutFromFld=Field.Make("From",#Field_Char,theOWidth,0)
theOutToFld=Field.Make("To", #Field_Char,theDWidth,0)
theOutDistFld=Field.Make("Distance",#FIELD_DECIMAL,15,2)
theOutFTab.AddFields({theOutIDFld,theOutFromFld,theOutToFld,theOutDistFld})
theOutShpFld=theOutFtab.FindField("Shape")

'**********************************************************
'Make a point list from the Origin and Destination themes,
'  validate the points, and create a shape for the resultant
'**********************************************************

theOriginBM=theOriginFTab.GetSelection
theOriginBMout=theOriginBM.Clone
if(theOriginBM.Count=0) then
  theOriginBM.SetAll
end
theDestBM=theDestFTab.GetSelection
theDestBMout=theDestBM.Clone
if(theDestBM.Count=0) then
  theDestBM.SetAll
end

if(theOutFTab.StartEditingWithRecovery) then
  theOutFTab.BeginTransaction
  pointList = {}
  for each rec in theOriginBM 'theOriginFTab
    p = theOriginFTab.ReturnValue(theOriginShapeFld, rec)
    theOriginName=theOriginFTab.ReturnValueString(theOriginLabelFld, rec)
    if (aNetwork.IsPointOnNetwork(p)) then
      pointList.Add(p)
    else
      msgbox.info(theOriginName +NL+"Not close enough to network",
```

```
            "Origin not located")
    continue
  end
  for each rec in theDestBM 'theDestFTab
    p2 = theDestFTab.ReturnValue(theDestShapeFld, rec)
    theDestName=theDestFTab.ReturnValueString(theDestLabelFld, rec)
    if (aNetwork.IsPointOnNetwork(p2)) then
      pointList.Add(p2)
    else
      msgbox.info(theDestName+NL+"Not close enough to network",
            "Destination not located")
      continue
    end

    findBestOrder  = True
    returnToOrigin = False 'True
    ' calculate the path
    pathCost = aNetwork.FindPath(pointList, findBestOrder, returnToOrigin)
    ' make sure the FindPath succeeded
    if ((not (aNetwork.HasPathResult)) or (pathCost = 0)) then
      msgBox.Error("Path not found.","")
    '  exit
      continue
    end
    aPathShape = aNetwork.ReturnPathShape

    theRec=theOutFtab.AddRecord
    theOutFtab.SetValue(theOutShpFld,theRec,aPathShape)
    theOutFTab.SetValue(theOutIDFld,theRec,theRec)
    theOutFTab.SetValue(theOutFromFld,theRec,theOriginName)
    theOutFTab.SetValue(theOutToFld,theRec,theDestName)
    theOutFTab.SetValue(theOutDistFld,theRec,aPathShape.ReturnLength)

    pointList.Remove(1)
  end
  pointList={}
  theOutFTab.EndTransaction
 end
end
theOutFTab.StopEditingWithRecovery(True)

theOriginFTab.SetSelection(theOriginBMout)
theDestFTab.SetSelection(theDestBMout)

theNetTheme=Theme.Make(SrcName.Make(theOutFName.Asstring))
aView.AddTheme(theNetTheme)
theNetTheme.SetVisible(True)
av.PurgeObjects
```

### C.2 Sidewalk Width Calculation

Sidewalk information is extracted from a table downloaded from MassGIS website: http://www.state.ma.us/mgis/mrd.htm. It is created by Mass Department of Highway with the sidewalk width of both sides of a road segment. The purpose of this calculation is to get the average sidewalk width along the paths I calculated.

Step 1: Create a grid layer based on the road polyline layer using the Assign Proximity function in ArcView. The value of each cell is the width of sidewalk weighted by the distance from the cell to the surrounding road network.

Step 2: Create a new table in ArcView with two columns. One is the ID of the paths from the path polyline layer, and the other one is for the value of average sidewalk width.

Step 3: Convert each path in the path layer into a grid layer, and assign a value of one to all the cells in the layer. Merge the path grid layer with the sidewalk grid layer to create a new grid layer. Sidewalk value will be transferred to the new layer. Sum the value for all cells and get the average.

Step 4: Transfer the average width to the new table and match the value with the corresponding destinations and trips.

Step 5: Go through the above process and calculate the width for all 2130 paths.

## Avenue Script ( by Zhan Guo )

```
**************************************************
'Crreate a New Table from the Path Layer
**************************************************
tablename = "Attributes of Left.shp"
  theDoc = av.FindDoc(tablename)
  if (theDoc = nil) then
    MsgBox.Info("Table 1 not found","Error")
    return nil
  end
 theVTab = theDoc.GetVTab

 theView = av.GetProject.FindDoc("View3")
 theTheme = theView.FindTheme("Left.shp")
 theFTab =  theTheme.GetFTab

 theGridTheme = theView.FindTheme("prox1")
 theGrid = theGridTheme.GetGrid
 theExtent = theGrid.GetExtent

 box = Rect.Make(theExtent.GetLeft@theExtent.GetBottom,
 theExtent.GetWidth@theExtent.GetHeight)

 cellSize = 10

 NewTable = "Sidewalk_2"

 theNewVtab = Vtab.makenew(NewTable.asFileName,dbase)
 MyTable = Table.make(theNewVTab)
 MyTable.SetName(NewTable)

 'add new fields
 f1 = Field.Make("ID", #FIELD_SHORT, 5, 0)
 f2 = Field.Make("AVESW", #FIELD_FLOAT, 5,2)

 theNewVTab.AddFields({f1,f2})

 theNewVTabIDCOL = theNewVTab.FindField("ID")
 theNewVTabSWCOL = theNewVTab.FindField("AVESW")

 theIDvar = theVTab.FindField("id")

*******************************************************
 Walk Through the Table, Updating the Records
*******************************************************
 for each i in 0 .. 219
   thePathID = theVTab.ReturnValue(theIDvar, i)
   'MsgBox.Info(thePathID.AsString,"")

*******************************************
 Select a Path and Convert into Grid
*******************************************
```

```
   aQuery = "[id] = " + thePathID.asString
   'MsgBox.Info(aQuery,"")
   theBitMap = theVTab.GetSelection
   theVTab.Query(aQuery, theBitMap, #VTAB_SELTYPE_NEW)
   aProjection = theView.GetProjection
   aGrid = Grid.MakeFromFTab(theFTab, aProjection, theIDvar, {cellSize, box})
   'vGTheme = GTheme.Make(aGrid)
   'vGTheme.SetName("G")
   'theView.AddTheme(vGTheme)


*****************************************************
Create a New Grid Based on Two Grid Layers
*****************************************************
   newGrid = aGrid.IsNull.Con(aGrid,theGrid)
   aNGTheme = GTheme.Make(newGrid)
   'theView.AddTheme(aNGTheme)

******************************************************
Calculate the Sum and Average Sidewalk Value
******************************************************
   sTable=aNGTheme.GetVTab
   valField = sTable.FindField("Value")
   coutField = sTable.FindField("Count")
   Totals = 0
   Totalt = 0
   t=0
   s=0
   for each rec in sTable
     s = sTable.ReturnValue(valField,rec) * sTable.ReturnValue(coutField,rec)
     t = sTable.ReturnValue(coutField,rec)
     Totals = Totals + s
     Totalt = Totalt + t
   end ' for each rec in sTable
   'MsgBox.Info(Totalt.asString,"")
   aveSW= Totals/Totalt
   'MsgBox.Info(aveSW.asString,"")

**********************************
Add the Value to the New Table
**********************************
   NewRec = theNewVTab.AddRecord
   theNewVTab.SetValue(theNewVTabIDCOL, NewRec, thePathID)
   theNewVTab.SetValue(theNewVTabSWCOL, NewRec, aveSW)

 end ' for each record in Vtab
```

### C.3 PFP Parcel Creation

There are two data layers: one is the parcel data layer and the other one is the path polyline layer. Since the two do not overlap with each other, thus can not use the merge function in ArcView. The method I use is to shift the path polyline to four directions: east, west, south, and north. The offset distance is 20 meters. Then merge the parcel layer with the four polyline layer and get four new layers. Each of the four layer record the number of total PFPs along the path polyline. I will choose the largest number of PFP and assign it to this path as its value. This value means the maximum PFPs you can encounter from one of the two locations of the path—left side or right side of the road. All parcel types can be found at **http://gis.mit.edu/metadata/oracle/stclass.html**

### C.4 The Specification Code for the Final Model (Model E)

The software used for a binary logit model is SST, or Statistical Software Tools by Dubin and Rivers Associates.

**File Name: Final.cmd**

```
spool file[transfer.txt]

read to [choice trantime diff diff_inv GOVT DTXG level school Round Hh_3
Few_car conce w_den dif_den w_sw dif_sw w_ter onlywcom both_com]
file[transfer.txt]

range obs[1-3140]
set one =1
set zero =0

logit dep[choice] ind[one trantime diff diff_inv GOVT DTXG level school Round
Hh_3 Few_car conce w_den dif_den w_sw dif_sw w_ter onlywcom both_com]
prob[t]
```

```
REM calculate likelihood ratio

REM Input Lb and L automatically
set L=3140*log(0.5)
set p=sum(choice)/3140
set Lc=3140*(p*log(p)+(1-p)*log(1-p))

set y=choice
set Lb=sum(y*log(t))+ sum((1-y)*log(1-t))

set rau=1-(Lb/L)
set rau_bar=1-(Lb-19)/L
range obs[1]
print var[rau rau_bar L Lb Lc]
range obs[1-3140]

spool off
```

**Appendix D: A Sample Form of the 1994 MBTA Subway On-Board Survey**

# MBTA Rapid Transit Survey Nº 172417

*We at the MBTA strive to deliver reliable rapid transit service that meets your needs. This survey will help us determine how rapid transit service (Red, Orange, Blue and Green Lines) can be improved. Please answer as many questions as you can. After completing the survey, you may hand it to a survey attendant, place it in a collection box at one of the downtown stations or drop it in the mail (no stamp is needed). Your answers are confidential and you will not be put on any mailing lists.* *THANK YOU!*

***Please answer the following questions after you get on the train:***

**1a. Which line were you boarding when you were handed this form?** 2

- ❑ Red Line
- ❑ Orange Line
- ❑ Blue Line
- ❑ Mattapan Trolley
- ❑ Green Line (subway only)
- ❑ Green Line B (Boston College)
- ❑ Green Line C (Cleveland Circle)
- ❑ Green Line D (Riverside/Reservoir)
- ❑ Green Line E (Heath/Lechmere)

**1b. At what station/stop were you handed this form?**

_______________ 3

**2a. Where did you start this trip?** ("trip" refers to *this one-way trip*)

- 4-1 ❑ At home
- -2 ❑ At school
- -3 ❑ At work
- -4 ❑ At the doctor or other personal business
- -5 ❑ At a store or shopping area
- -6 ❑ At a social or recreational activity
- -7 ❑ Other _______________

**2b. Where is that located?**

5 _______________
(city/town/neighborhood, and state)

6 _______________
(address or nearest street intersection or landmark)

**3a. Where did you first board a public transit vehicle on this trip?**

- 7-1 ❑ Where I was handed this form
- -2 ❑ At a bus stop located at _______________ 8
  on route (number or name) _______________ 9
- -3 ❑ At commuter rail station _______________ 10
- -4 ❑ Other _______________ 11

**3b. How did you get from where this trip started to that station/stop?**

- 12-1 ❑ Walked directly (from home, work, school, etc.)
- -2 ❑ Drove or rode and parked at or near station
- -3 ❑ Was dropped off
- -4 ❑ Other _______________

**3c. How long did it take to get to that station/stop?**

13 __________ minutes

**4. Approximately what time did you board this train?**

14 [ : ] 15-1 ❑ am -2 ❑ pm

**5. How did you pay your fare for *this* train trip?**

- 16-1 ❑ Token(s) or adult cash fare
- -2 ❑ Adult monthly pass (circle one):
  Local Bus; Subway; Combo; Combo Plus; Zone 1 or higher 17
- -3 ❑ 10-Ride ticket (Riverside Line)
- -4 ❑ Senior citizen or persons with disabilities reduced fare
- -5 ❑ Child/student reduced fare
- -6 ❑ Visitor Passport
- -7 ❑ Other _______________

**6. How long did you wait at the station/stop for *this* train?**

18 ____________ minutes

**7. At what station/stop will you get off *this* train?**

______________________________________________ 19[ | | | ]

**8a. Where will your entire one-way trip end?**

20-1 ☐ At home
-2 ☐ At school
-3 ☐ At work
-4 ☐ At the doctor or other personal business
-5 ☐ At a store or shopping area
-6 ☐ At a social or recreational activity
-7 ☐ Other ______________________

**8b. Where is that located?**

21 ______________________________
(city/town/neighborhood, and state)

22 ______________________________
(address or nearest street intersection or landmark)

**9a. On this trip, from which station/stop will you leave the public transit *system* (not just this train)?**

23-1 ☐ Where I get off this train
-2 ☐ At rapid transit station ____________________ 24[ | | | ]
on the ______________ Line 25[ | ]
-3 ☐ At a bus stop located at ____________________ 26[ | | | ]
on route (number or name) ____________________ 27[ | | | ]
-4 ☐ At commuter rail station ____________________ 28[ | | | ]

**9b. How will you get from that station/stop to your destination?**

29-1 ☐ Walk directly (to home, work, school, etc.)
-2 ☐ Drive or ride in car parked at or near station
-3 ☐ Get picked up
-4 ☐ Other ______________________

**9c. After you leave the public transit system, how long will it take you to get to your final destination?** 30____________ minutes

**10. How many days a week do you usually use MBTA rapid transit?**

31-1 ☐ Less than 1 day
-2 ☐ 1 day
-3 ☐ 2 days
-4 ☐ 3 days
-5 ☐ 4 days
-6 ☐ 5 days
-7 ☐ 6 days
-8 ☐ 7 days

**11. How many trips will you make today using rapid transit, other than this one?** (e.g., if you make a return trip later today, that would be one)

32 ____________ other one-way trips

**12. What is your age?**

33-1 ☐ 17 or under
-2 ☐ 18 - 24
-3 ☐ 25 - 34
-4 ☐ 35 - 44
-5 ☐ 45 - 64
-6 ☐ 65 or over

**13. Do you have a driver's license?**

34-1 ☐ Yes -2 ☐ No

**14. Did you have an automobile available for this trip?**

35-1 ☐ Yes -2 ☐ No

**15. What is your primary occupation?**

36-1 ☐ Professional
-2 ☐ Tradesperson
-3 ☐ Clerical
-4 ☐ Retail/Sales
-5 ☐ Homemaker
-6 ☐ Student
-7 ☐ Retired
-8 ☐ Unemployed
-9 ☐ Other____________

**16. What is your gender?**

37-1 ☐ Male -2 ☐ Female

**17. How many people are in your household, including yourself?**
(that is, the number of people living in your apartment or house)

38 ____________

**18. What is your annual combined <u>household</u> income?**

39-1 ❑ Under $20,000 -3 ❑ $30,000 - $39,999 -5 ❑ $60,000 - $79,999
-2 ❑ $20,000 - $29,999 -4 ❑ $40,000 - $59,999 -6 ❑ Over $80,000

**19. How many vehicles (cars & trucks) are owned by your household?**

40-1 ❑ None -4 ❑ 2 vehicles -7 ❑ 4 vehicles
-2 ❑ 1 vehicle -5 ❑ 3 vehicles -8 ❑ 5 or more vehicles

**20. What are your main reasons for riding the MBTA?** (Please check as many as apply.)

41 ❑ Convenience 45 ❑ Cost of parking downtown
42 ❑ Speed/travel time 46 ❑ Environmentally responsible
43 ❑ Comfort/relaxation 47 ❑ Only transportation available
44 ❑ Other ______________________

**21. If rapid transit were not available for this trip, what would be your most likely means of transportation?**

48-1 ❑ Drive alone -5 ❑ Other MBTA service (bus, commuter rail, ferry)
-2 ❑ Bicycle -6 ❑ Carpool/vanpool
-3 ❑ Private bus -7 ❑ Would not make trip
-4 ❑ Walking -8 ❑ Other ______________________ 49 ❑

**22. Several measures of service quality are listed below. Please circle a number after each measure to indicate how you feel about the service on *this* rapid transit line.** (Leave blank if not applicable.) **Then, place a check mark beside the 3 measures most important to you.**

| | | very poor | | average | | very good | ✔ |
|---|---|---|---|---|---|---|---|
| 50 | Station condition | 1 | 2 | 3 | 4 | 5 | 62____ |
| 51 | Station cleanliness | 1 | 2 | 3 | 4 | 5 | 63____ |
| 52 | Parking availability | 1 | 2 | 3 | 4 | 5 | 64____ |
| 53 | Personal safety at station/on train | 1 | 2 | 3 | 4 | 5 | 65____ |
| 54 | Vehicle security at lot/garage | 1 | 2 | 3 | 4 | 5 | 66____ |
| 55 | Cleanliness of trains | 1 | 2 | 3 | 4 | 5 | 67____ |
| 56 | Reliability (I can count on getting there on time) | 1 | 2 | 3 | 4 | 5 | 68____ |
| 57 | Explanations of delays | 1 | 2 | 3 | 4 | 5 | 69____ |
| 58 | Announcement of station stops | 1 | 2 | 3 | 4 | 5 | 70____ |
| 59 | Availability of seating | 1 | 2 | 3 | 4 | 5 | 71____ |
| 60 | Frequency of service | 1 | 2 | 3 | 4 | 5 | 72____ |
| 61 | Travel time/speed | 1 | 2 | 3 | 4 | 5 | 73____ |

**23. Have you ever complained to the MBTA in writing or by phone?**

74-1 ❑ Yes -2 ❑ No

**If yes, did the MBTA respond within 2 weeks?** 75-1 ❑ Yes -2 ❑ No
**was your complaint handled satisfactorily?** 76-1 ❑ Yes -2 ❑ No

**Comments/Suggestions:**